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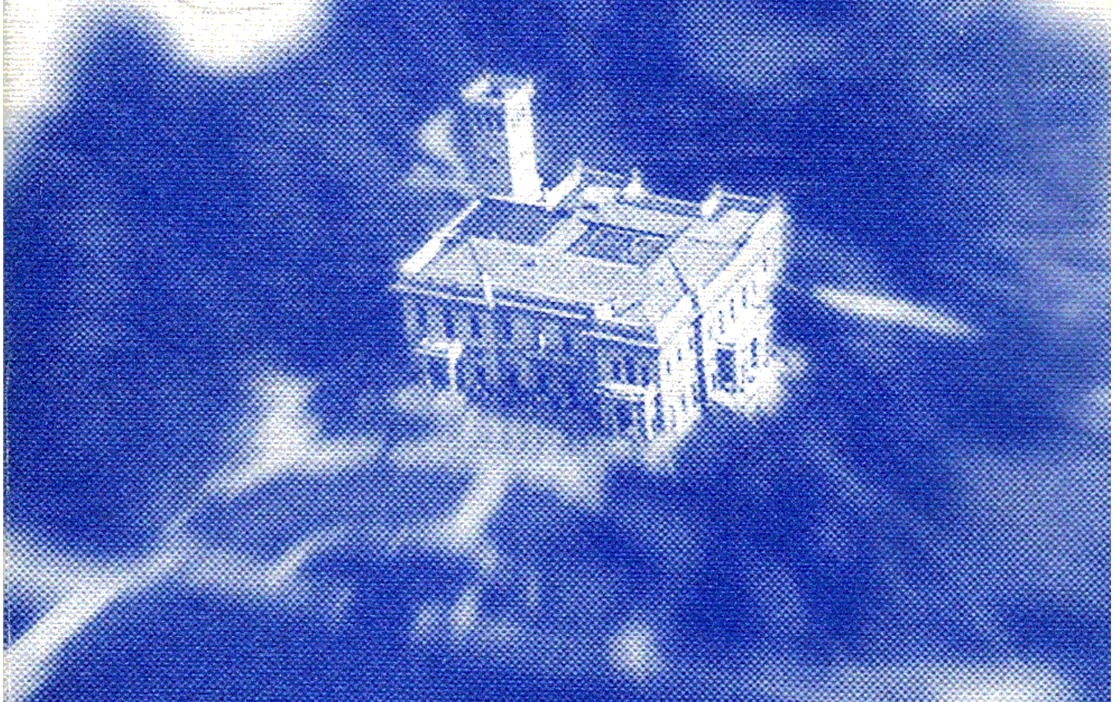

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Dynamic Vehicle Control for Enclosed Narrow Vehicles

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Brink Dynamics

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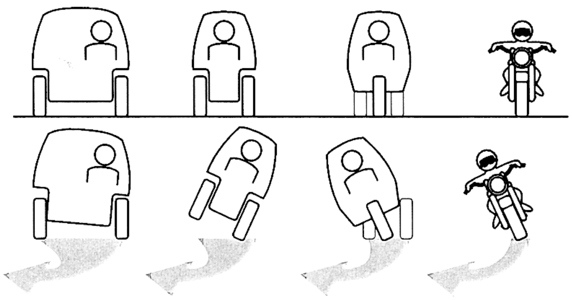


An enclosed narrow vehicle (ENV) for tandem, single/duo transport could offer an efficient vehicle alternative.
Because existing technology has not been able to solve problems relating to stability and overturning, vehicles half of the width and half of the weight of traditional cars have not formed a practical transportation alternative.
During 5 years of intense R&D, the Dutch company Brink Dynamics, a division of the Brink Technology Group B.V., has developed a revolutionary vehicle balancing system which can technically realise the vision of Enclosed Narrow Vehicles. The Dynamic Vehicle Control (DVC) system translates the 'car-type' steering input of the driver into the optimal 'motorcycle-type' tilt of the chassis. DVC enables an ENV to automatically bank through curves and to participate safely in traffic. When DVC is installed, an ENV becomes extremely stable, and drivers do not need sophisticated driving or balancing skills. The DVC system can realise a new breed of sensational vehicles which offer superior road-handling and are energy efficient. Brink Dynamics has installed the DVC system in several mechanical prototypes which perform beyond all expectations and will license her technology to interested parties.

1. The Gap Between Transportation Demands and Current Vehicle Alternatives

Currently, only three practical transportation options exist for travelling reasonable distances: public transportation, automobiles, or motorcycles. For many travellers, public transportation offers insufficient access, freedom, and schedule flexibility. These people must then consider a mode of personal transportation and choose between a comfortable, inefficient 2x2 car or a less comfortable, less safe but more efficient motorcycle. Because people prefer comfort and protection, they most often choose a car. Unfortunately, statistics show that more than 90% of all cars travelling from A to B are transporting only one or two persons and three empty seats. A 2x2 car wastes an enormous amount of energy and provides more capacity than the traveller actually needs. A definite gap exists between the individual's demand for transportation and existing transportation alternatives.

An enclosed narrow vehicle (ENV) for tandem, single/duo transport could offer an efficient alternative and reduce harmful emmissions by at least 40%. Because existing technology has not been able to solve problems relating to stability and overturning, vehicles half of the width and half of the weight of traditional cars have not formed a practical transportation alternative.

The Dynamic Vehicle Control (DVC) system developed by Brink Dynamics, a division of the Brink Technology Group, overcomes existing technical barriers and can enable manufacturers to produce an innovative class of enclosed narrow vehicles that can satisfy user needs and desires. An ENV can fulfil the market demand for a comfortable and safe single/duo transportation alternative and offers the following advantages:

- A unique, sensational driving experience
- Drives like a traditional car (no additional driving skills)
- Top acceleration, comfort and safety comparable to the 'middle-class car'
- Greater agility in traffic
- Safe and predictable, even under difficult road conditions
- Reliable and fail-safe
- Mass production costs less than a traditional car
- Energy efficient (1:33 ECE mix), lower road taxes
- 40% lower emissions (fuel propulsion system). Possible to install all innovative propulsion technologies to combine the advantages of propulsion and form.

Market opportunity analysis indicates that many occupations and circumstances within private, commercial and institutional sectors inherently demand single/duo transportation and could benefit from an efficient transportation alternative. Innovators who enjoy a sensational driving experience, commuters, police forces, post and delivery services, park-and-ride systems, car-sharing programs, traffic patrols, service/maintenance vehicles and military missions are just several examples of potential market segments.



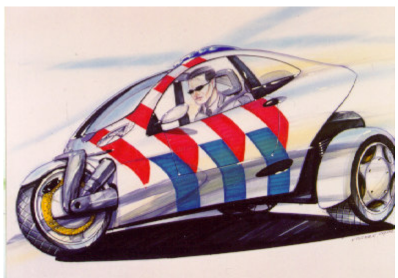


Fig. 1. Potential ENV applications

2. ENV Development Approaches

In 1883, the first patent was registered regarding an attempt to stabilise a narrow vehicle: 'Manually controlled support wheels'. Since the 1880's, many efforts have been made to develop a stable, narrow vehicle. ENV development can be divided into 3 principle approaches:

1) The 'Low and Slow' approach -- By reducing vehicle height in accordance with the reduction in width and by limiting the top speed and cornering speed, a 3-wheeler or a 4-wheeler can become an ENV with limitations which render the vehicle impractical for modern traffic situations. Example: Messerschmidt.

2) The 'Motorcycle' approach -- When riding a motorcycle, the rider must ensure that the centre of gravity always remains in line with the two contact points on the road. Under normal conditions, a motorcycle is relatively easy to drive and control. In difficult situations (e.g. slippery road), however, the required driving skills often exceed the driver's skills, which results in a loss of control. An enclosed motorcycle demands very sophisticated driving/balancing skills, requires support wheels for slow speeds and stopping, and is also subject to uncontrollable skidding out and overturning. Example: Eco-mobile.

3) The 'Tilting 3 or 4 wheeler' -- To compensate for lateral stability, the vehicle has some kind of tilting system to enable it to lean into corners like a motorcycle. If the leaning is controlled by the driver, the driver must try to calculate the correct tilting angle when cornering, which can require very sophisticated driving skills -- particularly in difficult or stressful driving situations, e.g. driving on slippery roads or when executing an evasive manoeuvre. This type of vehicle cannot be safely or predictably driven by the average person, which makes it an undesirable vehicle for mass production. Example: General Motors 'Lean Machine'.

3. The Brink Dynamics Approach -- Dynamic Vehicle Control

In a safely designed vehicle, eyelevel should not be lower than that of the other traffic participants. To realise a vehicle with a height of 1.5 m and a width of ~ 1 m, which will corner safely and with the same speed as the other vehicles in traffic, the vehicle must be designed to bank automatically through the curves. An automatic tilting system which could control the banking angle of the vehicle could allow the driver to steer the vehicle just like a traditional car.

The Dynamic Vehicle Control (DVC) system can technically realise the vision of enclosed narrow vehicles. Brink Dynamics has installed DVC in a mechanical testmodel and has developed the first ENV that can be driven just like a car. After a very short adjustment period, testmodel drivers begin to enjoy the natural feel of automatically banking through curves.

DVC is based on the phenomena which is present in every motorcycle front wheel, yet may not be apparent to motorcycle riders. When a motorcycle has the right combination of speed, bank angle and steering angle, the steering torque on the front wheel is zero. Any change in these three basic parameters results in a steering torque on the front wheel. If the steering torque is measured and the torque appears to be non-zero, then the vehicle is not in its correct tilted position. Depending on the sign of the steering torque, the DVC system increases or decreases the angle of banking towards the optimal position. When the optimal position is attained, the steering torque will reduce to zero and the actual tilting position will be maintained.

In effect, the DVC system translates the ‘auto-type’ steering input of the driver into the optimal ‘motorcycle-type’ tilt of the chassis. DVC enables an ENV to automatically bank through curves and to participate safely in traffic. When DVC is installed, an ENV becomes extremely stable, and drivers do not need sophisticated driving or balancing skills.

4. Basic DVC System Design

Brink Dynamics has tested the innovative principle of ‘Steering Torque Results in Tilting’ in several technical testmodels. As shown in **figure 2**, the basic DVC system requires only a few components to achieve an automatically tilting ENV.

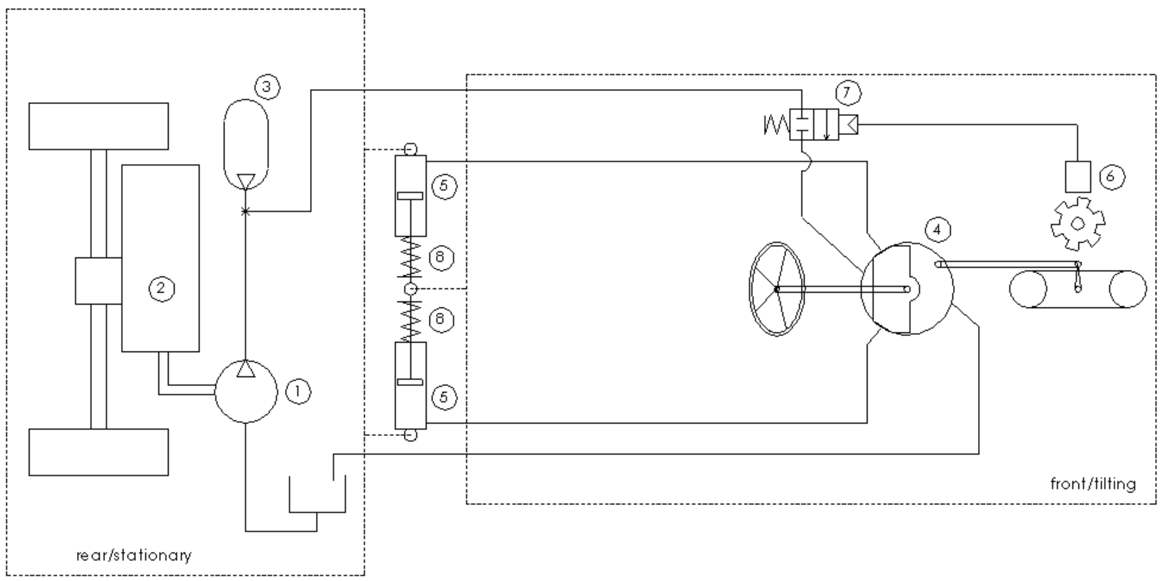


Fig. 2. Minimal components for a DVC system

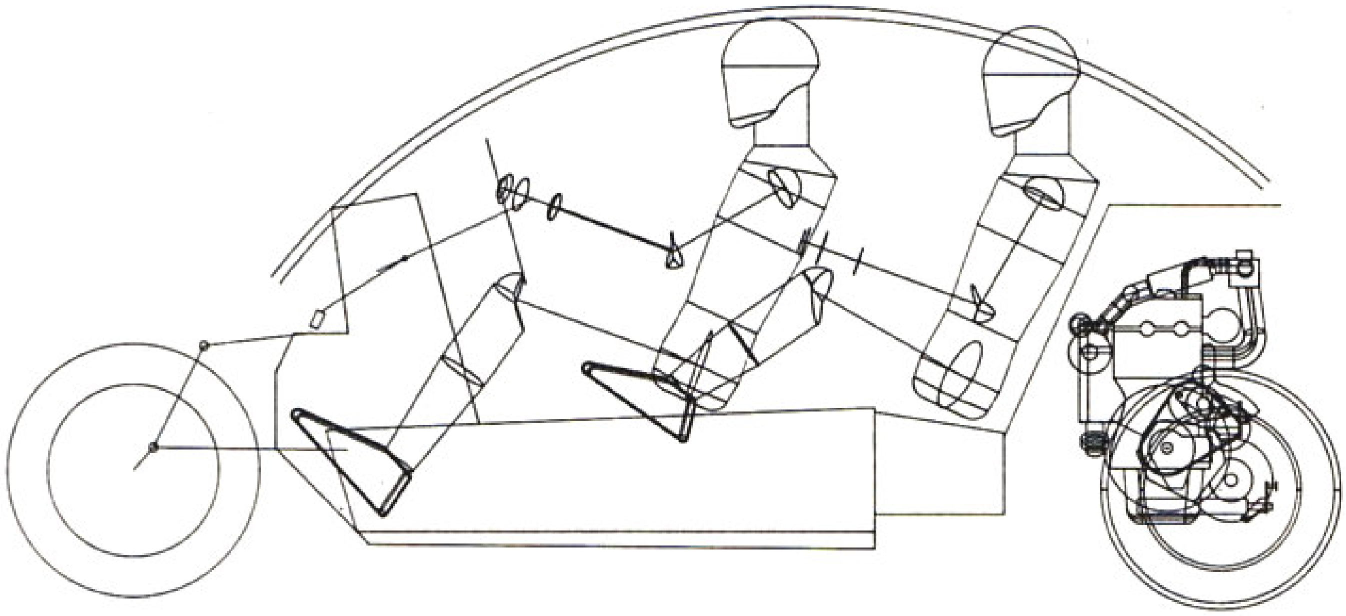
A hydraulic pump (1) is connected to the crankshaft of the engine (2). Combined with an accumulator (3) hydraulic system pressure is maintained (at ≈120bar). The steering valve (4) measures the torque between the steering wheel and the front wheel and controls the two hydraulic cylinders (5). The movement of these cylinders determine the leaning position of the vehicle. Because the road friction between the front wheel and the road causes too much disturbance on the tilting system, a speed sensor (6) activates a shut-off valve (7) to disengage the tilting system under 10 km/h and in reverse.

Brink Dynamics has chosen to use a fully hydraulic DVC system for several reasons:
- proven technology in a car-environment (power steering)
- reliable and durable
- predictable in failure
- high energy-density, high peak output

In the case of a hydraulic failure, two basic safety measures are built into the system. First, two springs (8) parallel to the tilting cylinders keep the vehicle upright in the absence of hydraulic pressure. Therefore, the vehicle will stay upright in the event of hydraulic failure or when parked. The second safety feature is inherently present in the front wheel geometry. When the tilting system is inactive, a large amount of trail makes steering very heavy. If system pressure drops, the driver immediately notices a change in vehicle response and can take adequate measures, i.e. stop.

5. Computer Simulation of Current Testmodel

The behaviour of the mechanical testmodel, a tilting three-wheeler, has been simulated in a multibody dynamic analysis. First, the maximum applicable tilting torque was determined. Primary factors are the distance between the rear wheels, as well as the weight distribution between front (tilting) and rear (stationary) parts. The tilt torque limit is reached when the inner rear wheel loses contact with the road surface. Based on actual vehicle dimensions and applied safety factors, the maximum applicable torque is 500Nm. With this available torque, the maximum tilting speed can be determined with relation to several vehicle parameters, e.g. vehicle speed, applied steering torque, and front wheel geometry.



General Dimensions			**Drivetrain & Performance**		
length		3.4 m	engine		660cc 4cylinder, intercooled turbo
width		1.15 m	max. power		47 kW at 7500 rpm
height		1.4 m	max. torque		100 Nm at 4000 rpm
wheelbase		2.6 m	transmission		5 speed manual + reverse
empty weight .		450 kg	top speed		180 km/h
max. weight		625 kg	acceleration 0-100km/h		7 sec.
Suspension					
front	type	double swing arm	**rear**	type	independent McPherson
	caster angle	65°			
	trail	13 cm			
	tire	130/60 ZR17		tires	165/60 R14
	brake	disc 330mm		brake	2x disc 250mm

Fig. 3. General dimensions of current Brink Dynamics testmodel

5.1 Vehicle Speed

Because of gyroscopic effects, as vehicle speed increases the tilting speed reduces **(figure 4)**. When a fast rotating motorcycle front wheel is being banked, it has the tendency to steer to the inside of the corner; therefore, tilting speed reduces when vehicle speed increases. Even in the case of an absence of an applied steering torque, there is a certain amount of car-type tendency for the front wheel to steer to the inside of a corner. This creates a countertorque which counteracts the tilting torque. Because this countertorque is directly linked to the tilting torque, the countertorque can at most prevent the tilting of the vehicle (at infinite vehicle speed) and can never make the vehicle unstable.

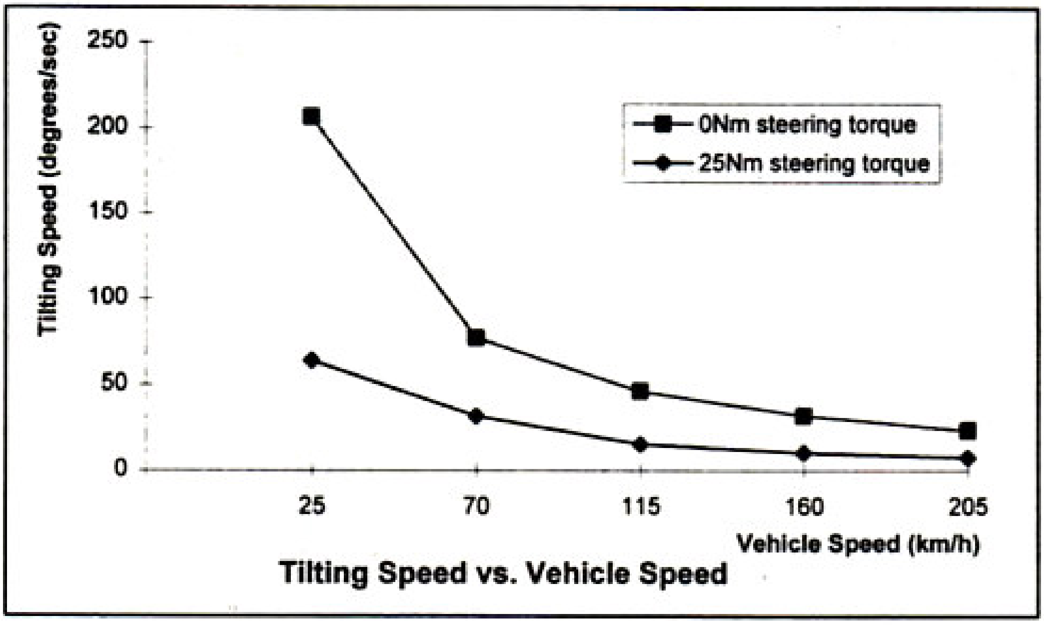


Fig. 4. Tilting speed vs. vehicle speed

5.2 Steering Torque

When the driver activates the tilting of the vehicle by a car-type steering torque input, not only the tilting torque is applied, but also a certain amount of car-type steering torque. This steering torque also generates a torque that counteracts the tilting torque. A steering torque of 34Nm fully neutralises the tilting torque of 500Nm **(figure 5)**.

The reason for this reduction is the basic difference between 'tilting before cornering' and 'cornering before tilting'.

'tilting before cornering' -- motorcycle
Only gravity is used to tilt a motorcycle to its desired position, after which the actual corner is initiated; the tilting speed of a motorcycle can be very high.

'cornering before tilting' -- any car with active suspension
After initiating the corner by turning the front wheels, the car body leans outward and has to be pushed to the inside of the corner by the active suspension system.

This 'pushing' against the centrifugal forces requires a large amount of energy; therefore, a 'motorcycle-approach' is preferred for a tilting vehicle. In order to reduce the centrifugal counterforce and thus increase available tilting speed, the car-type steering input of the driver must be kept to a minimum.

A steering torque of 25Nm is acceptable for adequate tilting speed **(figure 5)**. In general, to increase agility, the steering torque must be kept to a minimum. When steering torque exceeds 35Nm, the available tilting torque is insufficient and the vehicle starts to tilt to the outside of the corner as tilting speed becomes negative**)**. The steering valve has been designed to be fully opened at an applied steering torque of 25Nm for a compromise between steering torque and maximum tilting speed **(figure 4)**.

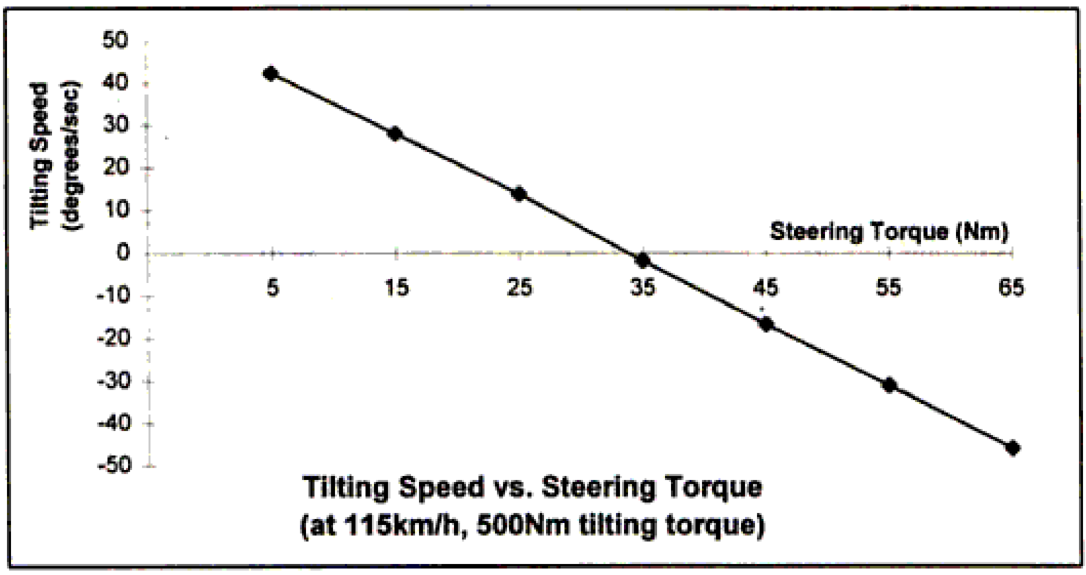


Fig. 5. Tilting speed vs. tilting torque

5.3 Front wheel geometry

One way to increase tilting speed is by increasing the front wheel trail. Gyroscopic coupling between steering angle and roll angle of the front wheel is drastically influenced by the amount of trail in the front wheel, resulting in a significant effect on achievable tilting speed.

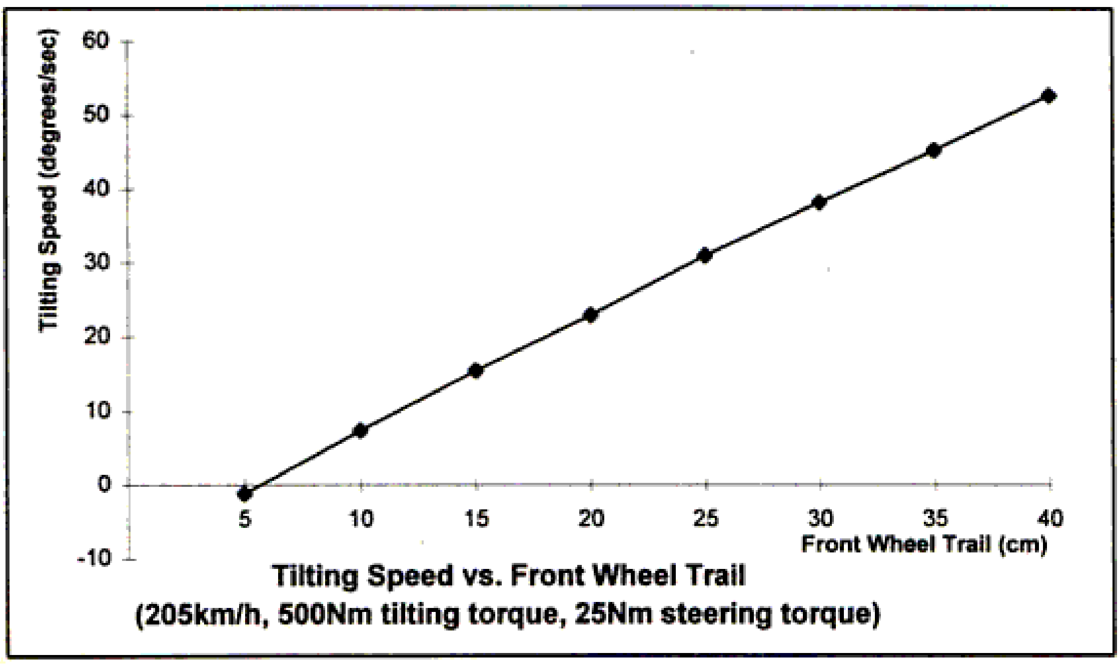


Fig. 6. Tilting speed vs. front wheel trail

6. The Advanced DVC System

To refine the characteristics of the basic DVC system (**figure 2)**, several components can be added. The advanced DVC system is installed in the current mechanical testmodel.

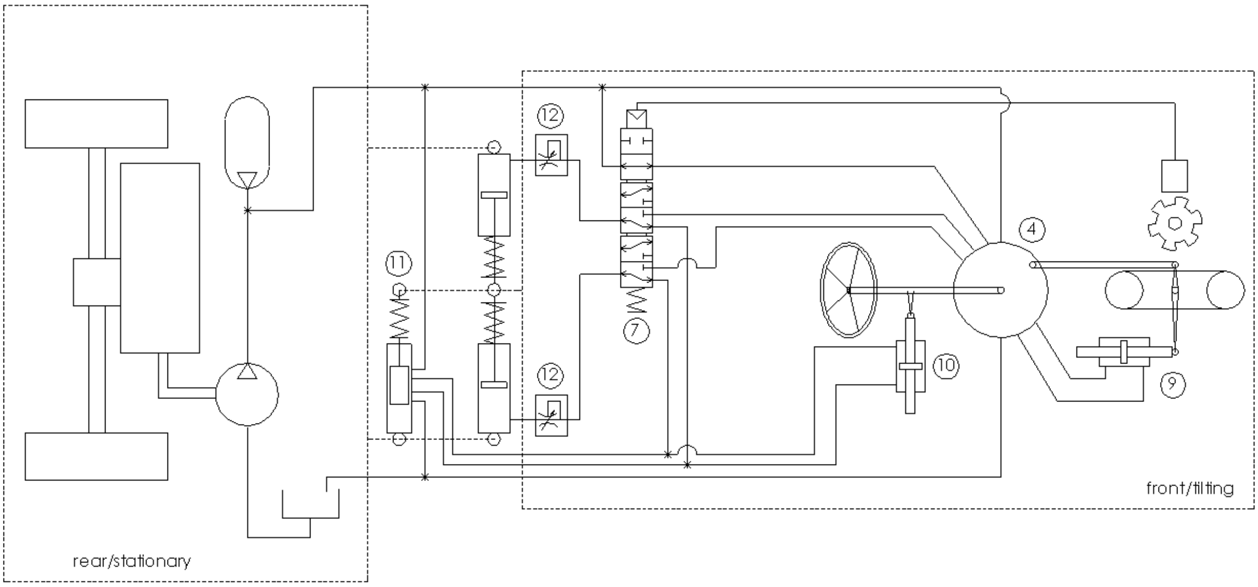


Fig. 7. Advanced DVC System

6.1 Power steering (9)

At normal driving speeds, steering forces are low because of the tilting system. At low speeds, the tilting system is inactive. Because of the large front wheel trail and the 1 to 1 steering ratio, steering forces are very high. At low speeds, a power steering system is activated to reduce the steering forces.

6.2 Steering Force Limiter (10)

As discussed in **5.2**, the maximum steering torque on the front wheel must be limited to 25Nm to limit the amount of 'car-type-cornering'. In normal conditions, tilting response is very quick and a small steering torque is sufficient to have full and accurate control over the vehicle.
In some circumstances, however, e.g. in a panic situation, the driver might give a large steering input. As shown in **figure 5**, such a large torque on the front wheel would drastically reduce the available tilting speed. To assure optimal vehicle agility in every situation, a steering torque limiter was built into the advanced DVC system.

When the driver applies a torque that exceeds 25 Nm, at which point the steering valve is fully open and tilting speed is at its maximum, another valve opens and puts a counteracting torque on the steering wheel. Therefore, the actual torque on the front wheel cannot exceed 25Nm -- independent of the torque the driver is putting on the steering wheel, which results in optimal vehicle agility and safety, even in panic situations.

6.3 Banking Angle Feedback (11)

In a normal car, the driver receives a lot of feedback concerning his cornering speed from the side force on his body. In a tilting vehicle, the driver is always in equilibrium and this side force is absent. The feedback the driver receives from his cornering speed is the increase in G-force combined with the visual clues of his tilted position. While testing the prototype, this feedback proved to be too little. Drivers began cornering at increasingly irresponsible speeds. To improve driver awareness, a hydraulic valve was developed that generates a torque on the steering wheel as a function of the angle of banking. This valve serves two goals: 1) the driver gets adequate feedback about his cornering speed; and 2) when releasing the steering wheel during a corner, the vehicle gradually returns to the upright position.

6.4 Steering Damper (13)

In principle, the steering valve has a linear relation between the steering torque and the pressure difference on the tilting cylinders. On an uneven road, this results in a very nervous vehicle. One way to smoothen the tilting response on the steering input is to place a damper in the steering valve. This damper slows the movement of the steering valve which results in a smooth beginning of tilting movement. The disadvantage of such a damper is the by-pass it creates around the steering force limiter, which reduces safety. Also, this damper introduces some hysteresis/overshooting, which deteriorates the general driver-vehicle interface.

6.5 Cylinder Damping Valve (12)

To correct the negative aspects of a steering damper, the steering damper can be replaced by a cylinder damping valve. To smoothen/dampen the tilting response in the cylinder line, a time-dependent flow-restrictor is present. When a steering torque is given, the flow restrictor starts in its low-flow setting and initial tilting response is very smooth. In about 0.2 seconds, the flow restrictor opens which gradually increases the tilting speed to its maximum.

7. Practical Experience with the Advanced DVC Testmodel

Brink Dynamics has performed several standard tests, which are common in judging the behaviour of a car.

7.1 Lane-change

As described in ISO/TR 3888-1975(E) a vehicle must be able to perform a lane-change with a lane offset of 3.5m at a speed of 80 km/h to be approved to drive on the road. When driving the testmodel, an inexperienced driver could manage 90 km/h after a few attempts. An experienced driver can manage speeds of over 100 km/h. Because the tilting torque and steering torque are limited, the vehicle shows no sign of any strange behaviour, e.g. lifting a wheel, oversteering, understeering, or breaking out at the front or the rear. In general, this manoeuvre can be performed quite effortlessly and smoothly; the DVC testmodel glides through the cones. A car driver would be straining to make these lane changes at higher speeds.

7.2 Braking

During braking tests with an unboosted brake system using a fully loaded testmodel (625 kg), the following figures were obtained:
- front and rear: 8.5 m/s^2 at pedal force 25 daN
- front wheel only: 4.0 m/s^2 at pedal force 15 daN
- rear wheels only: 5.0 m/s^2 at pedal force 46 daN

If the wheels are locked when driving in a straight line, the testmodel reacts exactly like a car. When the front wheel is locked in a sharp corner, the vehicle has the tendency to come upright and slides out on its front wheel. Apart from the tilting, this gives the same feeling as in a car. Normally, locked rear wheels never occur because of the weight and brake force distribution between front and rear wheels. If the rear wheels are locked during high speed cornering, the rear breaks out. If the driver does not correct this in time (using same correction technique as in a car), the vehicle will spin into reverse, in which situation the tilting system does not work. If, however, the Automatic Braking System (ABS) is installed in a DVC controlled ENV, then this potential problem can be avoided just like in a car.

7.3 High-Speed Handling

The reduced tilting speed at higher vehicle speeds **(figure 4)** is clearly demonstrated in the testmodel. Above 80 km/h, the testmodel remains stable and easy to control. Tests have been performed up to speeds of 180 km/h, and the testmodel continued to become more stable and solid-feeling. For the average driver, it is preferable not to be able to tilt at an angle of 45 degrees in 0.5 sec at 180 km/h. However, fast tilting at high speeds can be improved by changing the front wheel parameters and installing a countersteer device, e.g. for racing.

7.4 Fast Cornering

During normal cornering up to 45 degrees of tilting, the vehicle has a slight feeling of understeer because of the ‘banking angle feedback valve’. When reaching the maximum tilting angle of 45 degrees, an attempt to further sharpen the corner by increasing the steering torque will only have effect up to the maximum steering torque of 25Nm. A higher applied steering torque will be fully counteracted by the steering force limiter and will create a feeling of understeer. The natural reaction in this situation is to slow down, which will sharpen the corner. Braking or accelerating in a corner does not change this behaviour.

7.5 Slippery Roads

During cornering on slippery roads, the front wheel will be the first to break out. Only if the driver gives too much throttle, will the rear wheels break out first (just like in a normal rear wheel drive car) which can be corrected using the same technique as in a car. When the rear breaks out in a corner, the front part of the vehicle maintains the correct tilted position -- independent from the steering correction required to compensate for the rear wheel slip.

7.6 Side Winds

In strong side winds, the front body leans into the wind like a motorcycle. The driver needs only to give a small steering torque to stay in a straight line.

7.7 Sloped Roads

Sloped roads and ruts are automatically compensated for by the DVC system; the driver will only notice a light steering torque. While driving along a sloped road (e.g. on the side of a bank or a dike), the chassis of the testmodel remains upright. If the tires could retain traction, even roads with a slope of up to 45 degrees could be mastered.

8. Conclusions

During 5 years of intense R&D, Brink Dynamics has transformed her innovative principle ‘steering torque results in tilting’ into a viable vehicle balancing system. Brink Dynamics has also successfully adapted the DVC system to other types of vehicles to increase lateral stability, e.g. an All-Terrain Vehicle (Quad). The Dynamic Vehicle Control system technically realises the vision of enclosed narrow vehicles. An ENV offers a comfortable, agile vehicle alternative which can fulfil the individual’s actual need for single/duo transport and society’s need to provide energy and emission efficient transportation alternatives.