DVC™ - The banking technology driving the CARVER vehicle class

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During the last 10 years a tilting technology has been developed and refined which enables and new class of tilting three- and four wheel vehicles. The DVC™ (Dynamic Vehicle Control) tilting technology keeps the tilting part of such vehicles in balance over a wide range of velocities, and is based on an integrated system combining improved versions of the two commonly applied approaches of tilt control: Direct Tilt Control and Steering Tilt Control. To improve its performance and user friendliness several additional functionalities have been added, such as Power Steering, Tilting Attenuation, Active Rear Wheel Steering and Tilting Feedback.

This has resulted in one integrated, compact and easy-to-manufacture system having very low power requirements. It provides the necessary feedback to the driver to create a natural feel on the steering wheel allowing the driver to quickly adopt this new way of driving. The system has proven reliable for over 5 year of actual road testing. As a result of this the CARVER™, the first tilting Slender Comfort Vehicle (SCV) in series production, recently achieved European Road Certification. The DVC tilting technology also allows other types of tilting vehicles and is therefore being offered to other parties.

Topics: A1,A3,A19 : Vehicle Dynamics Control, Suspension Control, Advanced Concept Vehicles

1. INTRODUCTION

The DVC™ system, developed by Brink Dynamics, is the banking control system enabling the existence of a comfortable vehicle class with a considerable smaller width. These narrow vehicles called slender comfort vehicles (SCVs) combine the positive aspects of a car (safety, comfort and luxury) with the positive aspects of a motorcycle (low weight, dynamic driving performance). Having lower drag and lower weight, SCVs show a significantly lower fuel consumption and lower emissions. SCVs also consume less space in traffic and when parking. In addition to these environmental and practical aspects these vehicles have shown an excellent and inspiring driving behavior, outperforming conventional cars on various aspects.

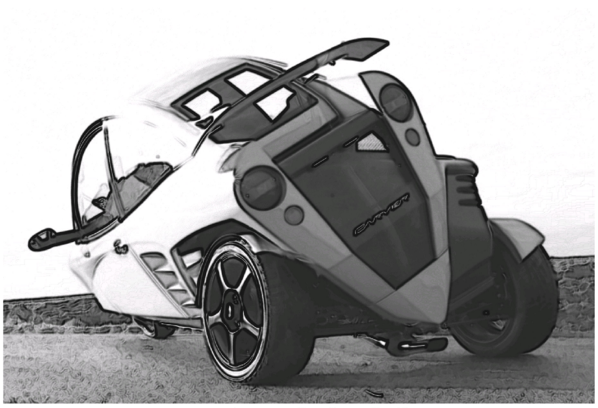

Fig. 1 Vandenbrink Carver

Since the breakthrough invention in 1994 the DVC banking technology, being the "heart" of the dynamic tilting system, has gone through a continuous improvement leading to a mature trouble-free system. The system is currently applied in the Vandenbrink Carver™ (Fig. 1, [12]), the first three wheel SCV vehicle commercially produced and marketed.

The DVC system is a hydraulic/mechanical control system managing the tilting angle of the vehicle and at the same time giving the necessary feedback to the driver. Compared to for instance electronically based systems the DVC system has many advantages such as low cost, reliability and quick response. As a result Brink Dynamics has achieved road approval for the Vandenbrink Carver™ according to EC-regulations whereas until today no other comparable system has successfully been built that passed road regulations test.

2. TECHNOLOGICAL CHALLENGE

Designing a tilting slender vehicle requires a non-conventional approach. When the width of a car is reduced to half, cornering becomes a problem, as slim vehicles are more prone to fall over (see Fig. 2). Of all the possible approaches, tilting when cornering is the

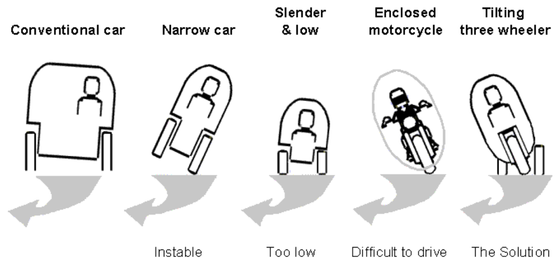

Fig. 2 Tilting when cornering

best option. This is actually what a two-wheeler does, and is nothing new. However, if one wishes to have the comfort and safety of a car, the vehicle needs to have an enclosed and solid passenger cabin. With such a cabin the balance control becomes more difficult for the driver, as the vehicle becomes too heavy. Also in that case the driver will be unable to put his/her feet out at low speeds to avoid falling over.

Therefore an automatic system is required to take over this balance control. As a result designing a tilting vehicle is not so much a package design problem, but first of all a technological problem requiring the development of a sophisticated automatic balance control system. In order to create a comfortable and safe vehicle, such a control system needs to generate the ideal tilting angle under all the imaginable driving circumstances, such as at all speeds and accelerations, during rapid emergency maneuvers, but also at slippery, irregular or slanting road surfaces. Furthermore it should also be predictable, intuitive and easy to use and last but not least it should be safe, reliable and fail-safe.

3. TILTING VEHICLES

The introduction into the technical aspects of the DVC technology can best be described by first reviewing the history of other attempts to create enclosed tilting vehicles, as this will describe the fundamental principles associated with such vehicles [9,10]. When regarding these technologies one can more or less classify these into two basically different tilting control principles, namely Direct Tilt Control (DTC) and Steering Tilt Control (STC).

3.1 Direct Tilt Control

With this principle, sometimes also called Active Tilt Control, an actuator is placed between the tilting part and the non-tilting part of the vehicle, or the actuator is integrated in the vehicle suspension. Various vehicles have been equipped with such a system, such as the Mercedes Lifejet F300 and the Project 32 Slalom.

The actuator allows control over the tilting position of the vehicle but requires some kind of feedback system to become self-balancing. The usual means to control this is by placing a lateral acceleration sensor in the tilting vehicle part. By doing so, the relative side-force can be measured and used as a signal to drive the actuator. A disadvantage of such a system is the delayed vehicle response and the risk of vehicle oscillations, thus requiring highly sophisticated loop control algorithms, which also need to be adaptive to different loads and driving conditions. Another inconvenience is the high power requirements to generate the required tilting motion, as the tilting must always act against the centrifugal forces.

Another possible DTC method is to provide foot pedals and let the driver control the vehicle tilting directly, without the used of an actuator. This system was applied in the GM Lean Machine. The limit of human muscle power however makes this approach only possible in lightweight vehicles, and also the control mechanism is not entirely natural which can lead to accidents in unexpected road situations.

3.2 Steering Tilt Control

The other principle to balance or tilt a vehicle is by using the method that is actually employed by every motorcycle rider: Proper steering of the front wheel on a free-tilting-vehicle allows the rider to control the tilted position (and the traveling direction). This control mechanism can be classified as 'differential' in the way that steering input of the rider induces a tilting movement that finally results in the desired balanced tilted position. This way of control requires significant learning and constant rider attention, but most people have learned this at a very young age and have no problems riding a bicycle or a motorcycle. A big disadvantage of STC is that balancing does not function at very low speeds or at a standstill, and in this situation you have to put your feet down, or, in the case of an enclosed vehicle, use some sort of righting mechanism (Honda Gyro) or a deployable outrigger system (Peraves Ecomobile). This discontinuity at low speed is the main obstacle in the acceptance of enclosed motorcycles. Putting your feet down is a simple and straightforward action on a normal motorcycle, but once the rider is put inside an enclosed vehicle, the 'feet down' functionality has proven to be virtually impossible to replace by a mechanical system. The problem here is not the building of a mechanism that locks the vehicle in an upright position below a certain speed. The vital hurdle is the discontinuity in vehicle behavior when switching from 'locked' to 'balancing'. In the locked situation, controlling the vehicle requires a straightforward 'steer to the right to go to the right'. But when the vehicle unlocks and switches to 'balancing mode', a steering input to the right will immediately flip the vehicle on its left side.

Another major disadvantage of any STC vehicle, either open or enclosed, is that in slippery road conditions the lack of tire friction makes balancing impossible, which may result in an unsafe situation.

4. DYNAMIC VEHICLE CONTROL (DVC)

The DVC system actually makes use of both principles to which several innovative improvements have been added. First of all, both the DTC and STC principle had to be improved:

4.1 Improved DTC

The acceleration sensor normally used in DTC can only sense a corner after the unbalance has occurred. As a result the system always is too late to optimally balance its actions. This problem can be overcome by using the steering torque as an input parameter. By doing so the driver cornering input can be measured directly, before the actual corner is taking place [1]. This allows a much quicker vehicle response, and makes it possible to tilt the vehicle even before the cornering has begun. This does not lead to instability because of the linkage with the front wheel and its motorcycle properties.

4.2 Improved STC

The disadvantages of the standard STC can be best overcome by taking the balancing responsibility away from the driver and letting an automatic system take care of the front wheel steering to control the vehicle balancing. This has the following benefits: First it allows disconnecting the driver steering input from the front wheel, which makes it possible to present the driver with a ‘simple steer’ interface: To make a turn to the right, he simply has to steer to the right. The improved STC system will now take care of the initial steering input to the left which is required to tilt the vehicle body to the right in order to make a balanced motorcycle corner. Secondly, this ‘simple steer’ approach also removes the discontinuity when switching from ‘low speed lock’ to ‘balanced driving’ as mentioned in paragraph 3.2 STC.

A tilting vehicle only relying on this improved STC approach would be extremely complicated to design, especially to allow it to drive at low speed. However, when integrated into the complete DVC system already based on DTC the implementation becomes less critical and more straightforward.

4.3 Dual Mode Tilt Control

Combining DTC and STC into one integrated system makes it possible to use the advantages of both systems, while the negative aspects are canceled out.

Most noteworthy, by adding the improved STC system to a DTC system, the system response to cornering becomes much faster and requires significantly less power [2].

The challenge for the vehicle designer is to create such a system that fulfills all requirements, while at the same time using proven technology in a low complexity package with high reliability and low manufacturing cost.

4.4 Optimal Driver Interface

Not only is it important to have a control system that safely controls the vehicle in all circumstances, also great care must be taken to provide a natural and comfortable interface to the driver. After a minimal learning phase, the driver must feel relaxed and in control, and the vehicle must react in a natural and predictable way to the driver inputs, both in normal conditions as well as in extreme road situations.

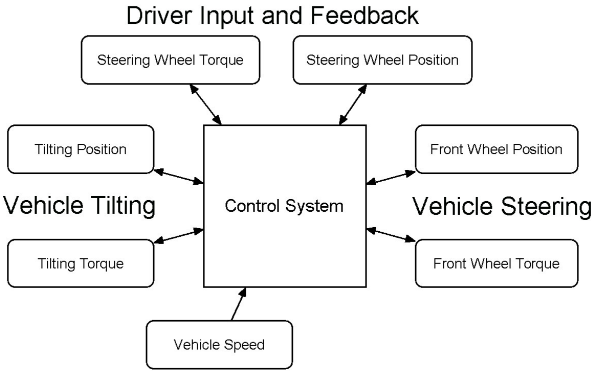

Fig. 3 Control strategy

5. DESIGN PHILOSOPHY

At first sight, one would think that the complex combination of position, movement and force feedback control would lead to a highly sophisticated sensing and computing environment, where using numerous feedback loops and response times are of critical importance. But this view is totally incorrect.

By using a design approach based on physical properties and fundamental dynamics, it is possible and in fact efficient to build a control system. This philosophy has been worked out in a hydraulic-mechanical system where the *steering input* of the driver is distributed between a *front wheel steering angle* and *a tilting angle* of the chassis. As a result a *triangular relationship* is created which causes all three variable to self-balance under all circumstances [3]. At varying speed and road conditions, the distribution between front wheel angle and tilting angle is always automatically adjusted, ensuring the optimal (balanced) situation under all circumstances [4, 5, 6].

At low speeds the driver’s steering input is fully directed to the front wheel and the vehicle remains upright. At higher speeds the steering input is more and more translated into a tilting angle and not into front wheel angle. As the DVC system uses a combination of hydraulic and mechanical technologies it shows a high reliability, quick response and a natural “feel”.

6. BASIC DVC TECHNOLOGY

The implementation of this philosophy in the commercial Carver is shown in Fig. 4 showing the main elements of the DVC system being the DVC manifold and a pair of tilting cylinders. The tilting cylinders (Fig. 7 item 2) are attached between the rear (non-tilting) part of the vehicle and the tilting front part of the vehicle (the passenger compartment) in such a way that activation of these cylinders causes a tilting action of the passenger compartment. The DVC manifold (Fig. 7 item 1), a hydraulic valve acting as the main sensor, measures the torque of the steering wheel relative to the front wheel, and depending on this torque pressurizes the hydraulic oil to one individual cylinder (dark lines in Fig. 4) and withdraws the oil from the counteracting cylinder. The resulting tilting action will lead to the release of torque on the front wheel, causing the pressure in the system to relax to normal pressure (light

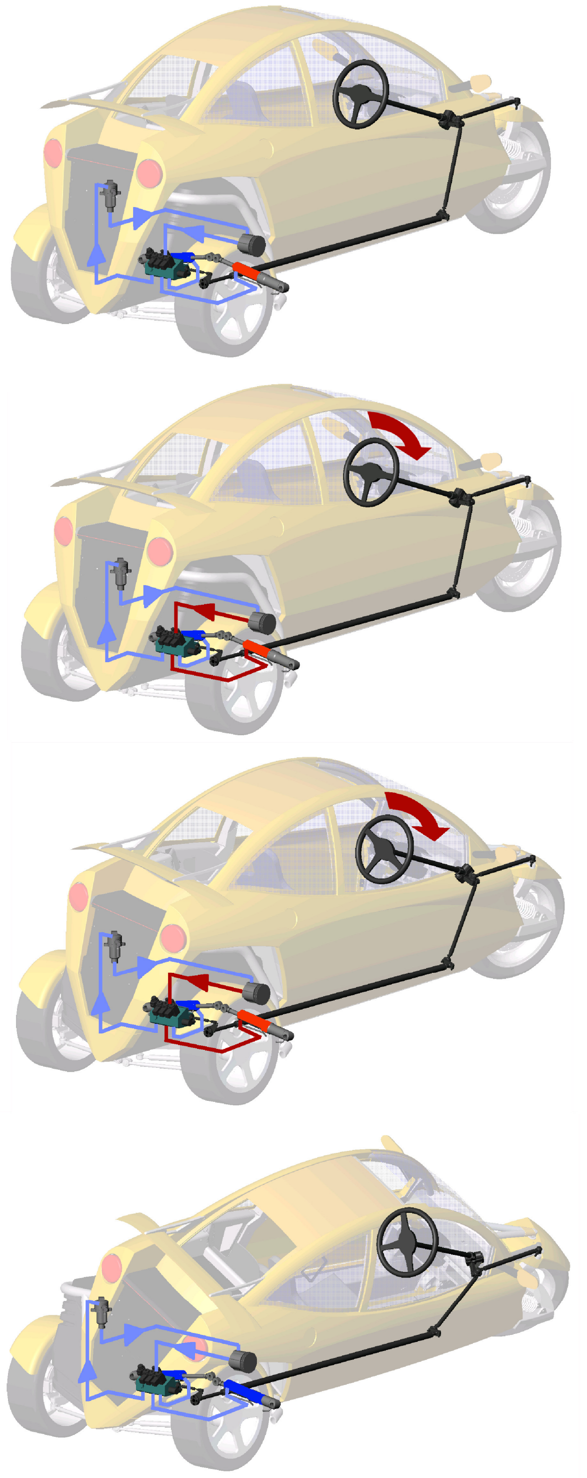

Fig. 4 DVC in action

lines in Fig. 4). As a result of this Improved DTC principle the passenger compartment always is in dynamic balance. A DVC system based on only this Improved DTC principle works highly satisfactory at speeds between 10 and 100 km/h with low to moderate cornering dynamic.

7. IMPROVEMENTS TO DVC TECHNOLOGY

To expand the envelope under which the tilting system operates satisfactory, several components and features have been added and/or integrated to this basic system. The numbers of these supplementary technologies are indicated in Fig. 5.

1) A low speed switch that turns off the tilting action below 10 km/hr. This system also acts as an emergency back up system using a fully independent stand-by hydraulic control.
2) Power steering for light and direct steering during vigorous steering actions at low speed (e.g. parking).
3) Tilting attenuation associated with speed to improve the transition between non tilting situation at low speeds and the tilting situation at high speeds.
4) Improved Steering Tilt Control, (also mentioned in paragraph 4.2) for an optimal vehicle agility and safety at vigorous steering situation at high speed, such as lane changes or panic situations. This feature increases the promptness of the system and also lowers its power consumption (Fig. 6, [7]).
5) Active rear wheel steering optimizing comfort and safety at high speed [8].
6) Banking Angle Feedback for a continuous interaction between driver and his vehicle, acting at all speeds.

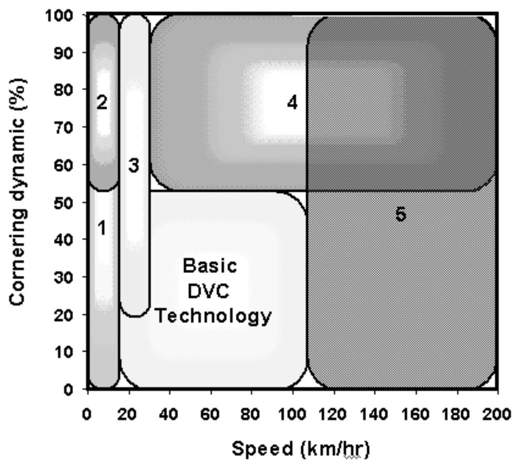

Fig. 5 Areas of improvement with additional technologies

As can be seen in Fig. 5 the active rear wheel steering and the Improved STC approach significantly widens the application range of a DVC system.

The positive influence of the Improved STC approach on both vehicle agility and DTC power requirements is clear from the test data in Fig. 6. A maximum slalom maneuver at 100km/h without STC requires the maximum available tilting torque of 1000Nm and results in a maximum tilting speed of 49°/sec, while with STC a tilting speed of 82°/sec requires only 100Nm tilting torque. This reduction in applied tilting torque corresponds with a power consumption for the tilting that is negligible. Applying more STC can even reduce the DTC tilting torque to

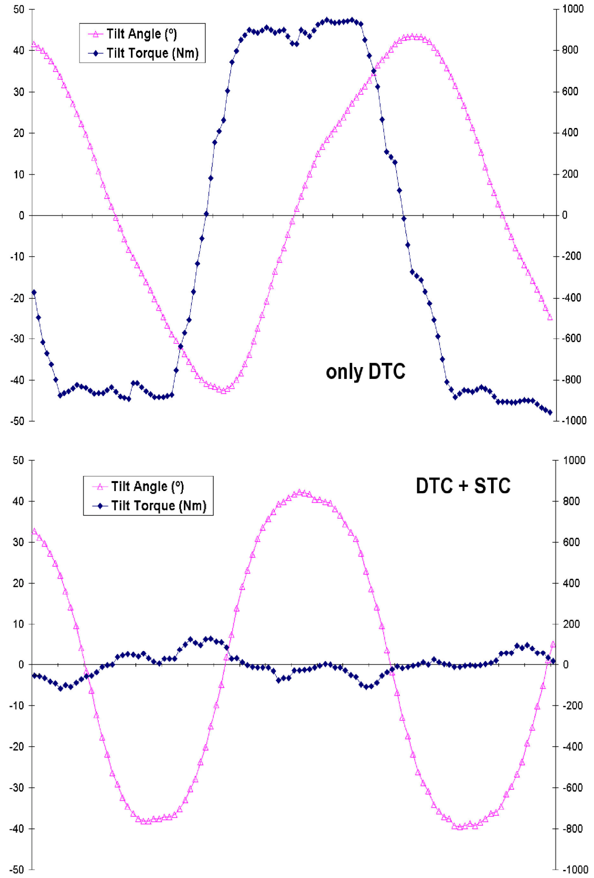

Fig. 6 Influence of STC on tilting

zero, but testing with such a setting has shown to be less comfortable for the driver.

Most of the above features and functionalities have been integrated into one single hydraulic DVC manifold which is shown in Fig. 7. By integrating this into one manifold the tilting hardware has become rather simple. In addition to the DVC manifold and the cylinders only a few other simple components are required to create a fully functioning system (Fig. 7).

The consolidated action of these features and components results in a driving performance that has a natural feel and is an enjoyment to drive. The system has a large degree of freedom to tune the characteristics of the tilting system. This allows adjustment of the overall character of the vehicle, enabling the existence of both aggressive and direct tilting vehicles as well as vehicles with a more comfortable and relaxed tilting characteristic.

The DVC system as employed in the CARVER provides a maximum tilting angle of 45° and a maximum tilting speed of 82°/s. This tilting speed figure is an important characteristic as it describes the promptness of cornering, especially in a chicane (lane change) situation. As a reference: On a conventional motor cycle, tilting speeds of this magnitude can only be achieved safely by highly experienced racing motorcycle drivers.

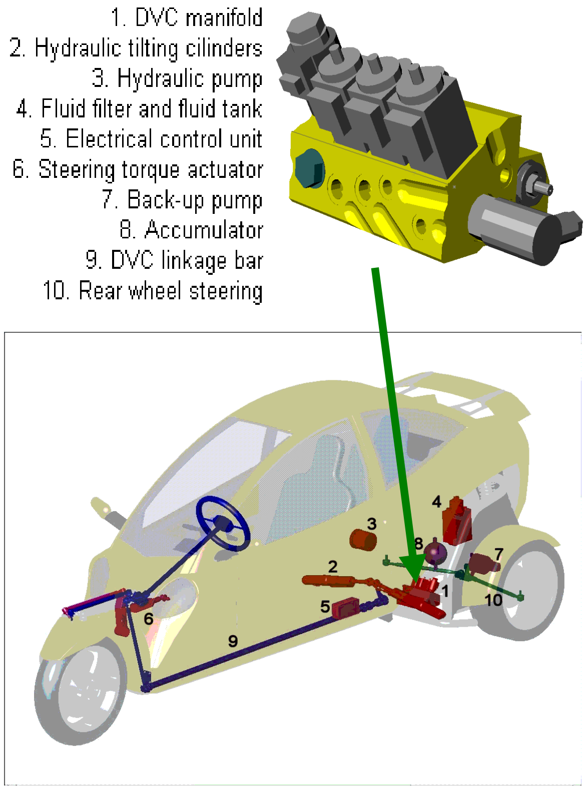

Fig. 7 The main components of the DVC system

The tilting function operates over the full range of 10–180 km/hr, the latter speed being the top speed of the CARVER.

With the DVC system vehicles can be designed having a width of 1 meter or even less. Due to the simple and straight-forward feed-back system the DVC system keeps on functioning properly even when one or more wheels start to skid, as can happen on slippery roads (rain, snow, gravel).

The complexity of the system is comparable to hydraulic power steering systems currently employed in conventional cars, with the weight for all components being less than 20 kg in total and the manufacturing cost around 400 Euro when mass produced. Under normal use the average power consumption of the DVC system is less than 0.1% of the total power requirement of the vehicle, and can be regarded as negligible.

8. CONCLUSIONS & FUTURE PROSPECTS

Thanks to the DVC technology tilting SCVs have now become a viable option to the transportation market. They show positive driving characteristics, which especially emerge positively on winding roads and in heavy traffic. In addition to these attributes, SCVs have lower drag and lower weight SCVs thus accomplishing significantly lower fuel consumption and lower emissions compared to conventional cars. SCVs also consume less space in traffic and when parking, making them ideal city vehicles.

For these reasons various car and motorcycle companies have recognized this new vehicle concept as a potential breakthrough to create a totally new market. These companies are now conducting feasibility studies in this area.

The DVC system and its underlying philosophy can also be used for tilting vehicles with wheel configurations different from the Carver, such as 4-wheel vehicles and 3-wheel vehicles with two wheels in front. The DVC approach has already been successfully installed on a tilting ATV Quad. Interested parties are invited to contact us to explore the possibilities of implementing the DVC approach into new families of vehicles [11].

Fig. 8 Tilting Quad in action

9. REFERENCES

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