Environment- Friendly Mobility

K. Hofer, *Senior Member, IEEE*

Abstract – **First of all this paper shows the typical consumption of energy of different transport systems and it answer the question what environment-friendly mobility means. Secondly it presents an electric vehicle on one wheel which has an energy consumption of less than doing a walk. This funny one-wheeler is powered by a three-phase electric drive system and stabilized by an observer-based gravity control. As four-quadrant electric drives are able to correct the tilt angle nearly one hundred times a second this smart vehicle can stand absolutely alone just like ghostly balanced. Unicycles are useable by kids, trendy people and creative workers during short trips in all areas of leisure, home, school, office, super markets, airports and cities.**

***Index Terms*-- Ecological formula, energy consumption, small electric vehicle, self-balancing, gravity control**

I. Introduction

Energy is a valuable good which we should use economically. In order to do so it is necessary to get a clear picture of the various forms of primary energy, the energy requirement and what it depends on. In the case of vehicles the consumption is determined mainly by the speed, secondly by the volume and thirdly by the mode of driving as well as by the luxury and comfort inside the vehicle. This can be described in an ecological formula which is valid for all transportation systems:

The slower, the lighter and the more spartanic a vehicle is, the more environment friendly its production and operation become.

One example of the best possible realisation of these ecological requirements is the well-known bicycle, which is very slow, absolutely light and extremly spartanic. Through being able to set energy free by means of switches, buttons, and accelerators, people have lost their feeling for the quantity of energy being used. And that although the human body itself is a very modest machine working on just 50 to 100 Watts by an efficiency rating less then 20 percents. It follows that very little energy is used for transport systems with biological motors. With a consumption of a half kilowatthour one can walk 20 km or cycle 50 km. The calculation uses the energy content of the energy carrier concerned, based on the international SI units systems.

$$1 \text{ Ws} = 1 \text{ Nm} = 1 \text{ J} = 1 \text{ kgm}^2/\text{s}^2 = 0{,}239 \text{ cal} \qquad (1)$$

The quantity of thermal energy released by one litre of petrol or one and a half kilogramms of coal or three cubic metres of municipal gas amounts to about ten Kilowatt hours thermal energy; that is 8.617 Kilocalories. With this amount of thermal energy one could take four showers or heat the family home in winter for a good hour. If this energy is turned into electricity by a generator, only four Kilowatt hours of electric energy is produced, and the remaining 6 kWh damage the environment because this part of energy cannot be used electrically.

$$\begin{aligned} 1 \text{ l petrol} &= 1{,}5 \text{ kg coal} = 3 \text{ m}^3 \text{ gas} = \\ &= 10 \text{ kWh} \quad \text{thermal energy} \\ &= 4 \text{ kWh} \quad \text{electric energy} \\ &= 3 \text{ kWh} \quad \text{mechanic energy} \end{aligned} \qquad (2)$$

If the electric current is transformed by means of an electro motor into mechanical kinetic energy, three kWh reach the motor's shaft. This is equivalent to 10,8 Mega-Newtonmeter, with which a body weighting one tonne can be transported exactly one kilometer in vertical direction. This level of effectiveness of 33 % is somewhat higher than in the case of combustion engines (approx. 15 %) in motor vehicles.

Fig.1 Environment-friendly electric vehicle on one wheel

Electric unicycle vehicles are very simple in their mechanical construction. **Fig.1** illustrates the general principles of such a light vehicle. It consists of a fork shaped frame, a broad wheel on pivoting bearings, and a variable speed electrical drive which includes an electric gear motor inside the wheel and the electric drive control plus energy storage inside the red box.. The power electronics and its controller change the electric motor one hundred times per second forwards and backwards in such a way that the centre of gravity of the vehicle and its rider is always vertically above the wheel axis. A fast sensor/ observer for the angle of tilt is provided for this purpose. It determines the deviation of the centre of gravity from the vertical, and

feeds it as the actual position to the centre of gravity or tilt controller. When stationary, the unicycle stands upright on the spot by means of very small alternating control movements. A secure support for the user is provided by treads which are mounted on the right and left underneath the axle.
Modest steerability is provided to the unicycle by phasing the outer edges of the wheel. The steer ability can be improved through the use of a rubber suspension to mount the wheel axle in the fork frame. In the same way as with roller skates, a displacement of the rider's centre of gravity to the right or the left makes it possible for the wheel axle to turn from the current direction of travel.

II. ENERGY CONSUMPTION OF TRANSPORT SYSTEMS

The energy required for various kinds of transport systems is shown in **fig. 2** in more detail. In order to be able to make a comparison the specific consumption must be related to one person (seat) and 100 km. Further, it must be assumed that each means of transport is full, as otherwise the consumption figured would be appreciably higher. As was to be expected, it is the bicycle that proves to use energy most economically because a cyclist can go 100 km on 1 kWh. According to fig. 1 this is equivalent to a petrol consumption of 0,33 litres per 100 km, or in American terms 720 mpg (miles per gallon). This is due on the one hand to the optimum ratio of the weight of the vehicle (20 kg) to its load (75 kg) and on the other to the low speed (20 km/h) and no comfort or luxury. By contrast, a distance of 100 km in a fully occupied aeroplane raises the energy consumed per passenger 12-fold. This makes aeroplanes the greatest energy wasters of all means of transport, so that their use should be reduced to an unavoidable minimum. The main reasons behind the ecological damage caused by aeroplanes are the high speeds (900 km/h) on the one hand and the comparatively high weight of the vehicle (in excess of one tonne per passenger) on the other. Extreme levels of 18 litres of fuel per passenger and 100 km are reached by supersonic passenger planes at speeds of 2,200 km/h (2.2 Mach).

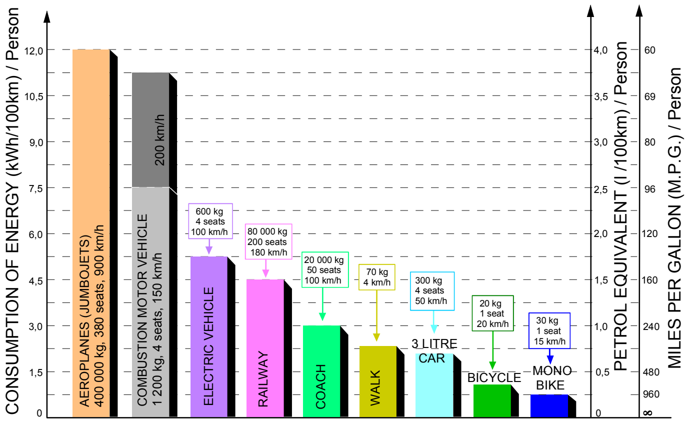


Fig.2 Energy consumption of different transport systems

Normal middle-class cars with combustion engines also waste energy extremly, as they use an average of 7,5 kWh per person and 100 km, which is equivalent to 2,5 litres of petrol per 100 km (or 96 mpg) and per person. The reasons for this are the high weight of the vehicle, horrendous acceleration values and high final speeds. If on short journeys the motor does not reach its operating temperature or the car is not fully occupied, then the energy consumption per occupant rises accordingly. In the case of a four-seater combustion-engine car with a final speed of 150 kmh (200kmh) the total energy consumption at the wheels of the vehicle amounts to 30 kWh (45 kWh) or a consumption of 10 (15) litres of petrol per 100 km. In American terms this is equivalent to 24 (16) mpg. From this consumption a motor performance of about 54 kW / 73hp (100 kW / 136 hp) can be calculated [1]..
Of course, any other vehicle with these characteristics would be found to reach the same level of energy consumption. The reason why many electric cars have a more favourable level of consumption (about 20 kWh), does not lie in any basic principles. It is simply the result of the vehicle's being lighter, its more modest motor performance (20 kW) and its much lower final speed of 100 km/h. But the fundamental advantage of the electric vehicle can be seen in the fact that the electric power can be generated everytime and absolutely environment friendly using solar cells , wind and hydroelectricity. The fact that it has no starters or clutches and does not have to warm up can be regarded as an additional advantage. Good average speeds and few brakings mean that railway systems result in the best possible traffic flow, which is reflected in a favourable energy consumption of 4,5 kWh per 100 km and passenger. In the case of highest velocity trains (Maglev) with final speeds of 500 km/h and above, the consumption levels can be in the range of aeroplanes. On account of its favourable speed and the good ratio of vehicle weight and weight of load, a fully occupied coach comes top of the class in energy saving.
Taking all this into consideration, the much-discussed three-litre (80 mpg) car can only be a light and slow vehicle, as the 9 kWh (12hph) of mechanical energy released from three litres of petrol do not allow for more. This means that in the case of a motor performance of 9 kW (12hp) 100 km must be driven in an hour for the vehicle to achieve this low level. This explains the extremely low per person consumption - a mere 0,75 litre per 100 km - of a four-seater three-litre car. This leaves no room for the accessory generator with a performance of 3 kW and more (1 litre petrol per hour) which is now regarded as normal, nor for servo booster, air-conditioning, stereo or lighting. Thus reducing consumption automatically means sacrificing volume, speed and comfort.
In the case of riding a bike these factors play a minimum role, resulting in the lowest level of energy consumption among the means of transport, namely one kWh to 100km (see fig. 1). A further ecologically friendly means of transport is walking, the energy consumption for which is calculated to be about 2,5 kWh per 100 km. With its energy requirement per person of 0,75 kWh, the presented monobike lies light under this biological way of moving. Of course such low consumption levels can not be achieved by small combustion engines because and also their dynamical behaviour is absolutely to slow for this high-tech application which will be described in the next capitel.
There is no basis for a large scale use of ecomobils in industrialized countries unless car purchasers change their ideas and stop expecting the greatest possible luxury, high speeds and ranges and generous, heavy chassis, or have this attitude changed for them by realistic petrol prices. Here it must be remembered that the Earth took 30 million years to

build up stores of fossile fuel. Plundering and burning these enormous reserves in a few decades will inevitably lead to the destruction of our natural environment, dependent as it is on a delicate balance. A high level of energy consumption is irreconcilable with environment friendly behaviour. The avoidance of a senseless waste of energy and relinquishing unnecessary luxury must determine present and future behaviour with regard to mobility and consumption.

If a walk's energy consumption of 2,5kWh/100km is the criterion of an environment-friendly mobility than three litre cars are the true answer. However these roofed mopeds are not the dream of proud car drivers but they only guarantees an ecological footprint of less than one earth.

III. MOBILITY ON ONE WHEEL

Conventional unicycles are mostly known from circus arenas because they can be used only by people with a lot of skill and experience. The reason is that unicycles are unstable in all directions. In order to stabilize these one-wheelers automatically and make they useable for all people there are two steps of modification necessary. First a proper stabilization in sideways directions can be reached easily by changing from a small to a broad wheel. A further advantage of this first modification is a good steering of the vehicle because of the stiffness of a broad air-filled rubber wheel.

A second development step requires a gravity-controlled high-dynamical electric drive which guarantees the automatically stabilization in forward and backward directions. The presented electric vehicle is powered by a four-quadrant dc-servo drive consisting of a permanent exited dc-motor and a 4q-chopper converter. The control of gravitation, speed and torque is done by an observer-based cascade structure which stabilizes the unicycle automatically and places the driver's position in such a way that the centre of gravity is always above the axle of the wheel. A forward or backward drive can be initiated by a slightly shift of the driver in forward or backward direction. That means this electric vehicle is driven, steered and broken only by body movements as the driver is subordinated to the inner speed and torque control. Electric unicycle vehicles are very simple in their mechanical construction. Fig. 3 illustrates the general principles of such a light vehicle. It consists of a fork shaped frame, a broad wheel on pivoting bearings, and a variable speed electrical drive which includes an electric gear-motor inside the wheel and the electric drive control plus energy storage inside the red box. The power electronics and its controller drive the electric motor one hundred times per second forwards and backwards in such a way that the centre of gravity of the vehicle and its rider is always vertically above the wheel axis.

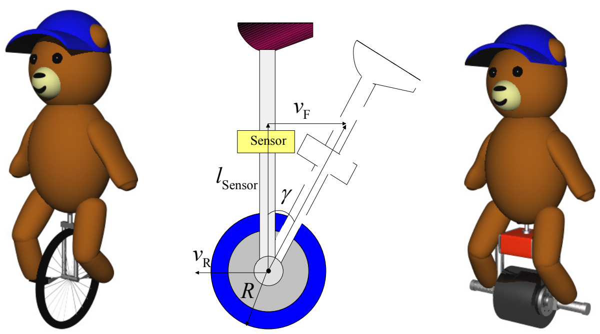


Fig. 3 Classical unicycle and electric unicycle

A fast sensor for the angle of tilt is provided for this purpose. It determines the deviation of the centre of gravity from the vertical, and feeds it as the actual position of the centre of gravity to the tilt controller. When stationary, the unicycle stands upright on the spot by means of very small alternating control movements. A secure support for the user is provided by treads which are mounted on the right and left underneath the axle [1].

The physical aspects and dependencies of unicycles are illustrated in fig. 3 in the form of an inverse pendulum. In upright state, its angle of tilt to the center of gravity is equal to zero ($\gamma = 0$). The angle of tilt, however, increases in proportion to the backward or forward tilt. The triggering momentum of an angular shift is either a certain velocity v_F by which the rider leans his body, and thus the seat, in forward or backward direction of travel, or a velocity v_R by which the wheel rotates in forward or reverse direction of travel, or, of course, a superimposition of both velocity components.

Assuming both velocities are equal in the value and sign, the angle of tilt will not change, i.e. the unicycle travels in upright position. A close approximation of small angles (γ) is:

$$\tan \gamma = \frac{s}{l_{Sensor}} \approx \gamma \qquad (1)$$

Allowances must be made for the triggering factor given by the distance between the sensor (l_{Sensor}) to the wheel hub (axle). The steering distance (s) between the seat of the unicycle to the vertical axis is determined by the integral of the velocity difference between the rider's seat (v_F) and the rotating wheel ($v_R = 2\pi Rn$). The steering angle is thus:

$$\tan \gamma = \frac{1}{l_{Sensor}} \int (\Delta v) dt = \frac{1}{l_{Sensor}} \int (v_F - v_R) dt =$$

$$= \frac{1}{l_{Sensor}} \int (v_F - 2\pi \cdot R \cdot n) dt \qquad (2)$$

This relationship confirms the assumption of the control of the angle of tilt formally being a common position control system, with an integral relationship between position and velocity based on the path-time law. A high-speed, precise measurement of the angle of tilt is of particular importance in the context of the automatic stabilization of unicycles by precise positioning of the center of gravity.

Prerequisite for controlling the stability of the unicycle in the direction of travel is a highly dynamic four-quadrant actuating drive which is capable of toggling forward and reverse motion in the milliseconds range. Those short reaction times automatically exclude the use of internal combustion engines or pneumatic drives.

Fig. 4 shows an efficient method of stabilizing unicycles by means of a closed-loop control system. The 4Q drive consists of an electrical motor and of a battery-powered 4Q power converter. An approach to a control concept could be a classic cascaded control loop structure, with an internal power control loop for torque control, and an intermediate velocity control loop for safety functions, both being integrated in the power control block. The outer angular tilt control loop feeds a torque set-point value to the power controller that outputs a manipulated value without any delay of the settling time, provided the highest permissible velocity, and thus the maximum speed of the unicycle, are not exceeded.

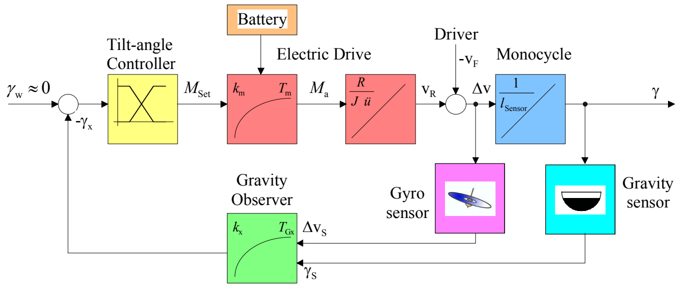


Fig.4 Observer-based control structure for an electric vehicle on one wheel

The tilt control is dedicated to maintain the angle of tilt (inclination) of the unicycle at zero by rapid reversals of the direction of torque in order to prevent the cycle from toppling. A small set-point (offset) compensates depressions in the road surface and measuring errors, and can be used to set the absolute standstill of the unicycle. The speed control loop reduces the torque set-point when the angle of tilt exceeds a certain maximum, for example, when the unicycle has toppled over as a result of a rider error, and the control system as to prevent any development of hazardous situations by the unicycle moving along the road at a high speed. The action of the rider is superimposed, so to say, as further process control variable on the torque control loop with secondary torque control and velocity monitoring. That is, the rider's action intervenes in the closed-loop control, in the form of a disturbance variable feed-forward, as shown in fig. 2, until the unicycle has reached the desired speed or position.
By a slight tilt of his body in the direction of travel, the rider shifts the unicycle out of the stable position, and thus forces a reaction of the tilt control. In order to prevent the unicycle from toppling, the drive therefore has to accelerate in positive (forward) direction until the deviation in the tilt control loop has been compensated. The motor velocity, and thus the speed of the unicycle, is variable, and is based on the rider leaning in the direction of travel to force acceleration of the drive. However, the velocity monitoring circuit should not directly intervene in the control loop when a speed limit is reached, because otherwise it is no longer possible to automatically stabilize the unicycle, and would cause it to topple over at full speed. An audible signal should warn the rider when he/she approaches the permissible speed limit.

IV. LOW-COST GRAVITY-OBSERVER

A solution for those measuring problems is provided by chip-sized gyro sensors, such as piezo sensors or spring-loaded gyro sensors for the high-speed detection of angular changes. However, the value of the angle of tilt required for this control loop must be derived from the integral of its rate of change, according to equation (2). To obtain a satisfactory stationary accuracy of the estimated angle, the mathematical formation of the model requires correction by means of estimate offset. When referring to such model algorithms, we speak of observers, a term commonly used in control loop engineering for various reasons. In low-cost automation engineering, the focus is set on simple and cost-effective observer software to replace expensive sensor hardware. Observers are commonly used in chemical plants, because of the complexity or impossibility of measuring certain process variables. Self-balancing unicycles require an integrated gravitation observer in order to generate measured values at a sampling rate of 100 Hz. Fig. 5 shows the simple low-cost structure of a gravitation observer of the first order. The gyro sensor measures the rate of change in the angle of tilt which is caused either by the movement of the rider or wheel, or as a result of the superimposition of both actions.

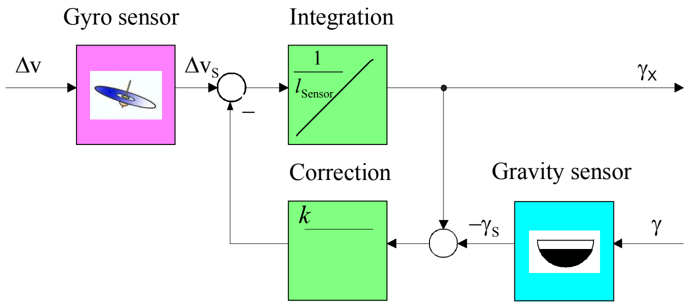


Fig.5 Structure of a state observer for fast estimating of gravitation

An integrator forms the actual value of the angle of tilt by summation. Stationary accuracy of the integration is given by the feedback of the estimate offset signal with the correction coefficient (k) which is formed by the difference between the estimated value of the angle of tilt plus the delayed actual value of the angle of tilt of a gravitation sensor. Both sensors shown in fig. 6 do not only react to changes in the direction of travel, but also more or less to lateral movements of the unicycle. Hence, it may be necessary to integrate further sensors in lateral direction to support the precise observation of the angle of tilt, and to compensate estimate errors based on this principle.
The dynamical accuracy of such a simple gravity observer is shown in fig. 6 for a short forward acceleration of the driver's seat. The upper curve shows the real angle of tilt during the movement. This true signal is measured by a variable resistant only for demonstration the observer's quality and dynamical behavior.

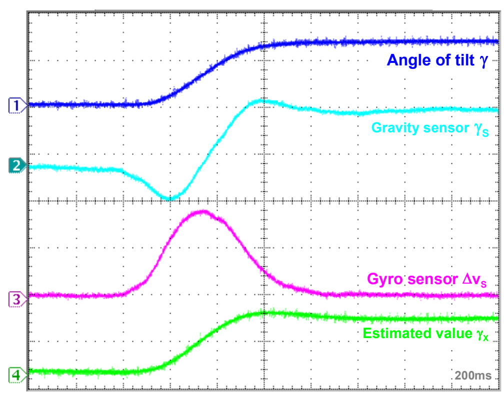


Fig. 6 Dynamical behavior of an observer for fast estimation of gravitation

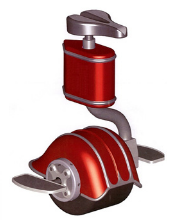
In the second curve of fig. 6 the time delay and measurement- error of a gravitation sensor could be clearly seen. The third curve shown comes from a gyros-sensor and corresponds to the angular velocity. The output signal of such a gyros-sensor is zero when the driver or vehicle are not moving. The lower curve shows the corrected output-signal of the gravity observer which is in good accordance with the real value of the tilt angle. This observed actual value is fast enough to be led to the tilt-control according to fig. 2 for the automatically stabilization of electric vehicles on one wheel or on one axle.

V. Conclusion

Energy is a valuable good which we should use economically. In the case of transportation vehicles we know the ecological formula: The slower, the lighter and the more spartanic a vehicle is, the more environment friendly its production and operation become. Normal middle-class cars with combustion engines also waste energy extremly, because of the high weight of the vehicle, horrendous acceleration values and high final speeds. If a walk's energy consumption of 2,5kWh/ 100km is the criterion of an environment-friendly mobility than a true three litre car is the only solution. However these roofed mopeds are not the dream of proud car drivers but they only guarantees an ecological footprint of less than one earth.

Today there are some environment-friendly electric vehicles in use. They all have only one wheel or one axle and can be met all over the world.





This self-balancing transport vehicles for one person are driven by kids, trendy people and creative workers mainly in the leisure and amusement sectors. Its small dimensions mean that the electric unicycles can be taken almost anywhere and used to advantage in cities, large buildings such as halls, airports, supermarkets, offices, home and other areas.

A computer animation and some video-clips about the presented one-wheeler will be shown during the conference.

VI. References

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VII. Biographie

Klaus Hofer was born in Karlsruhe in Germany, in August 1949. He studied electrical engineering at the University of Karlsruhe, attained his doctorate from the University of Siegen and habilitated at the University of Bielefeld, all in Germany. After graduation Dr. Hofer began his career as a development engineer at a global company in the area of observer-based drive control. In 1985 he tooks up the post of professor at Bielefeld in the field of power electronics and modern electric drives.

Professor Hofer has published twelve books, over 60 technical papers and he holds five patents, such as Binary Observers, Linear Cars and Unicycles. As a speaker and chairman he has participated in a lot of international conferences all over the world. Dr. Hofer is Senior Member and reviewer in the IEEE as well as evaluator in the industrial research (AiF). Furthermore he has adopted thirteen children from eight poor countries and founded a brain platform in the internet.