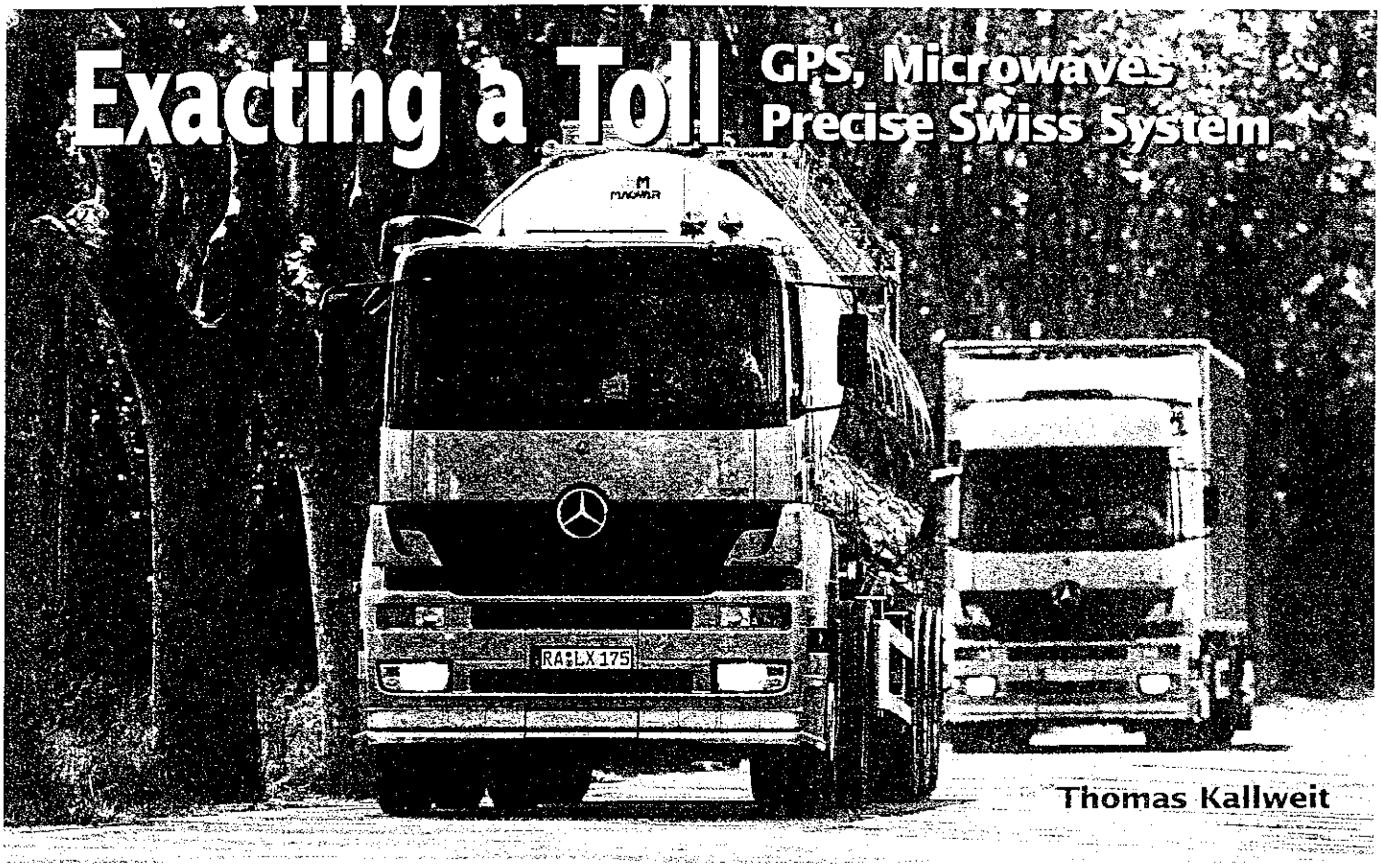


Exacting a Toll: GPS, Microwaves Precise Swiss System

Thomas Kallweit

Germany and Britain will implement satellite-based road tolling for trucks. The European Commission proposes mandating GNSS-based tolls throughout Europe. Meanwhile, Switzerland has already introduced a new road-tolling system for heavy vehicles, calculating fees according to distance travelled. An on-board unit combines a GPS receiver, microwave receiver, odometer data, and smart cards.

Thomas Kallweit *is a technical project manager at Fela Management AG in Diessenhofen, Switzerland.*

Driving in Switzerland has a different look nowadays. In the window of an approaching truck, you will usually see bright yellow lights, in bars of various patterns — evidence of the two-year-old Swiss heavy vehicle road-pricing system and its onboard unit using GPS technology.

New rules from the Swiss Customs Authority (OZD) required installation of these onboard units (OBUs) in every Swiss truck during the year 2000. More than 80,000 OBUs have been manufactured, and 60,000 Swiss trucks and an increasing number of foreign trucks that regularly pass through Switzerland now carry the devices. Tax revenues generated by the system totaled more than €500 million in 2002. This will rise to €1 billion from 2005 onwards, due to an increase of the tariff per kilometer.

When the initiative began in 1995, several key decisions shaped system specifications and the subsequent design of a new multifunctional onboard unit.

System Requirements

The Distance-related Heavy Vehicle Fee (LSVA) system calls for:

- payment of vehicle tax for travel over the entire Swiss road network, not just the motorways
- fee calculation based on the total number of kilometers driven in Switzerland; the registered net weight of the truck; and the truck's Euro class (pollutant class)
- payment, in addition to the distance-related toll, of a fixed fee for travel on certain roads — the Alps transit passages (many freight trucks travel between Eastern and Western Europe, and Northern and Southern Europe, via Switzerland)
- incorporation of a dedicated short range communication (DSRC) 5.8 Ghz microwave link for possible interoperability with existing and forthcoming systems
- foolproofing the OBU against manipulation or fraud. In the case of an external power cutoff or failure, the unit must record driving information

for at least six months.
- an optical display viewable from outside the truck, for enforcement purposes.

GPS-based Prototype

The first OBU concept that we developed was almost entirely based on GPS and some additional sensors for dead reckoning. We believed that with GPS we could:

- precisely record kilometers driven, and thus taxable, in Switzerland
- switch the tax mode off when the truck left the country
- keep installation procedures simple
- get the unit price below €350
- build a simple and easy-to-operate OBU that would collect reliable data.

In 1997, Fela developed five fully-functional prototypes. The OBU needed only a power connection to the vehicle battery and an additional connection for automatic recognition of added truck trailers.

Border Recognition. A key step in calculating distance driven within Switzerland is of course knowing when a vehicle is in Switzerland and when it is not — thus, border recognition. Prior to the start of the project, a competing firm stated that it had gotten the required vector data for the Swiss border from around 2 Mbytes down to a size of 30 Kbytes. At that time, our microprocessor in the prototypes had a maximum planned read-only memory (ROM) size of 60 Kbytes!

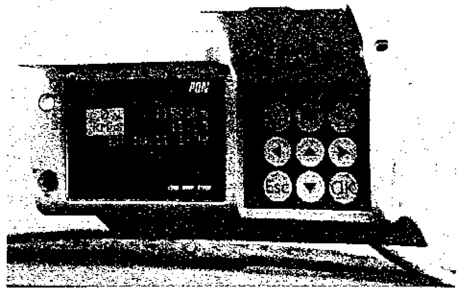
We managed to bring the size of the whole Swiss borderline down to less than 7 Kbytes without any negative effects on performance. The size is still of some importance, making it possible today to transfer the entire border data on a simple 8-Kbyte memory chip card into the OBU.

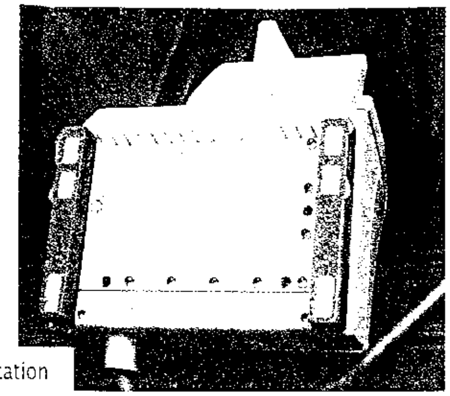
Chip cards are used in the system to send the collected data to the OZD taxation office. Each time the cards are sent back to the truck owner, they can be loaded with data for updating the OBUs.

The first prototype handled only a single borderline. The Swiss OBU in operation today contains two border lines, producing a corridor zone from 100 meters to 2 kilometers in width, influencing certain functions of the OBU when entering or leaving Switzerland.

With a single borderline, there is only "in" or "out" status. A corridor enables additional OBU functionality, for example, to unlock the in/out switch for manual declaration, or to give certain warnings if the declaration is missing.

The cross-border algorithm presented a problem at first. We tried both ordinary and quite complicated formulas, but we needed more efficient and compact code. At one point we had the idea of searching through algorithms developed for computer games. There we found useful input to substantially speed up calculation time. As soon as the OBU obtains a valid GPS position fix, it

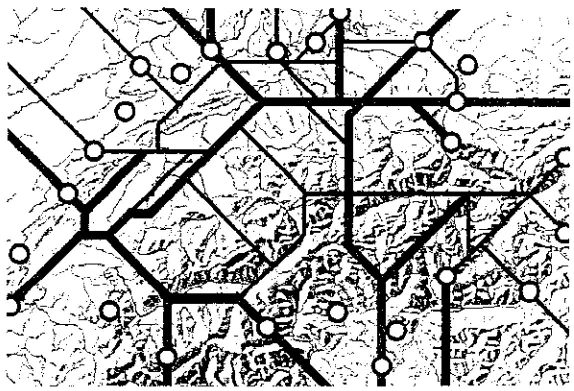




OBU viewed from inside the truck (left).

OBU viewed from outside the truck (above)

DSRC	Dedicated short-range communication
HVF	Heavy vehicle fee
LSVA	Distance-related heavy vehicle fee
OBU	Onboard unit
OZD	Swiss Customs Authority



Main Swiss roadways and border crossings

instantly knows the status and the area it is in. There are no delays to detect the inside or outside of Switzerland or the border corridor.

For the final OBU, we designed new hardware based on a 16/32-bit microcontroller containing an ARM7 core. This new hardware and fast algorithms enable the OBU to handle far more vectored geodata than would be needed for the Swiss application alone. This has important implications for new tolling systems such as those in Germany and Austria.

Cost. Installation costs represent a significant and critical part for any onboard car or truck equipment. Even though, under the Swiss system, the truck owner gets the OBU for free, it doesn't make sense to pay more for its installation than the unit's cost.

Bearing this in mind, we decided to incorporate everything necessary into the unit itself — including the GPS antenna. This substantially reduced installation cost, but in turn created the problem of efficient isolation from high-frequency noise of the truck's digital electronics.

We also anticipated that having the GPS antenna on the dashboard in the truck's front window would produce poorer GPS signal conditions. It turned out that, in general, we received one to two fewer satellites with the dashboard-placed antenna than with a roof-mounted antenna

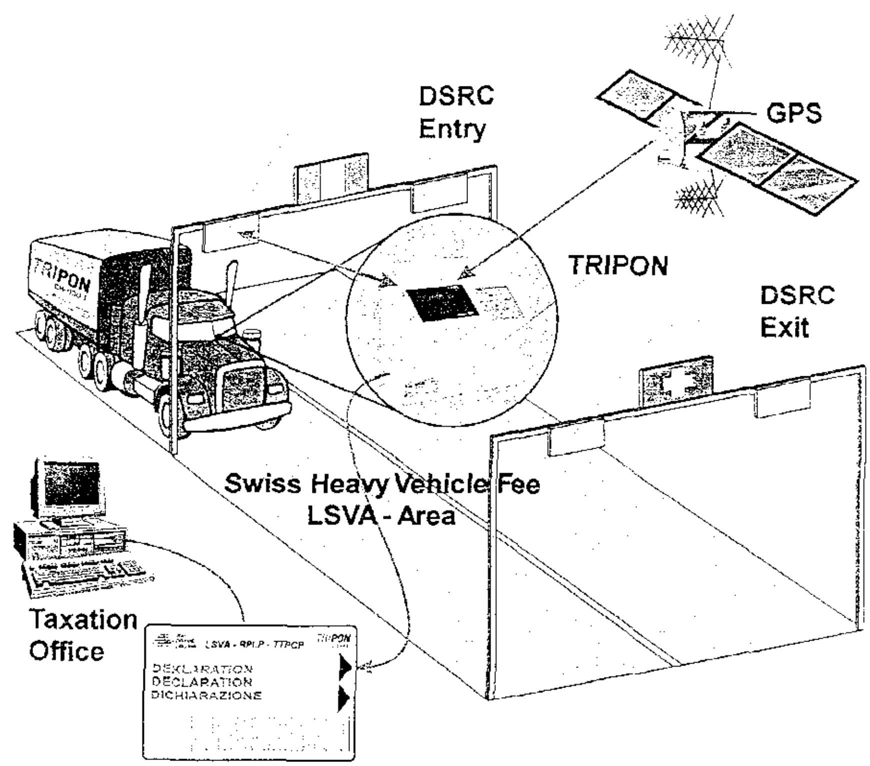


FIGURE 2 LSVA principle of operation

Microwave transmitters atop gantry at border control point

Testing

During prototype testing (1995–1999), *GPS* selective availability (SA) had not yet been turned off. Although GPS performance was still acceptable under these conditions from our point of view, the OZD decided that it was not reliable enough for use as the primary and sole mechanism. We discussed many ideas of extending the unit's software with enhanced dead-reckoning algorithms and/or *map-matching mechanisms, but in the end the* OZD chose a solution using microwave communications (DSRC).

This provided further benefits:

- Transmitters at every border cross give an instant feedback at the point of switching for the truck driver as well as the customs officers
- DSRC is absolutely independent of GPS.
- DSRC can be used for other purpo es *such as enforcement.*
- It opens the possibility for interop ability with existing European motorw tolling based on DSRC 5.8 Ghz.

Now truck border crossing can be declared

- automatically by DSRC
- manually by pressing a button on OBU
- or, the customs officers can use the special chip card to change the mode.

If the declaration is not changed correctly at the border crossing, the OBU's built-in GPS will first remind the driver *that the unit's mode is wrong, and then* unlock the special button for manual de laration dependent on whether the OBU is in Switzerland, in the corridor zone, outside Switzerland. If the discrepancy continues, it will trigger a log event registering t border crossing and its border-vector ID for late correction by the taxation office.

When exiting the GPS corridor leaving Switzerland, the GPS also switches off the unit's light bars, visible from the outside, if they haven already been turned off through proper declaration at the customs border control office.

Distance Recording

Precisely *recording the distance driven by the* truck — the basis for toll collection — posed qui a problem. As mentioned earlier, for the prototy phase we relied only on the GPS signal, knowing that there can always be some GPS signal blockage, and that in particular the cold start situatio would present difficulties. It is also easy to block or disturb the very weak satellite signals, openin up many ways of manipulating the system.

We needed some sensor signal to estimate the distance travelled, or the actual speed of the veh cle to calculate the distance over time. Existing accelerator sensors that we looked at didn't fit ou needs. Mathematically integrating acceleration *measurements* produced large errors in a rather short time. The additional requirement to recorc driving information even if unit power was cut o meant that we needed a sensor system which ha to run on about 200 µA, including running the microcontroller for data recording.

Recording data on a GPS basis, even using all of the most sophisticated power-saving tricks, *would never have worked.* In the prototype units we finally used two piezo sensors, one to detect the movement of the truck by analyzing the low

...ency acceleration, and a second sensor for estimating vehicle speed by analyzing the medium frequency range.

During driving phases under good GPS conditions, the sensor signals are calibrated by the GPS output. During absence of GPS signals, the sensor signal can be used to estimate the driving distance.

To get the optimum of the whole sensor system in terms of function, power requirements, and space, we developed a mixed-signal application-specific integrated circuit (ASIC) combining analog and digital parts.

Now we got a completely independent internal signal representing the driving status and vehicle speed. In normal GPS operation, the sensor system works as a kind of dead-reckoning device concerning the driving distance. The sensor also fulfilled the demand to operate on a single 3.6Vdc Li battery of 2 Ah for at least six months and collect driving data. The sensor system worked well, as shown in **Figure 3**. After a short period of driving the sensor signals get more and more calibrated and precision gets within demanded range.

GPS to Backup Role

During the prototype development stage, the OZD made another very important decision, that the main kilometer-counting had to be taken from the odometer or tachometric pulse of the vehicle. Legal reasons, primarily, led to this decision. The OZD wanted to rely on the well-regulated "infrastructure" in the truck, making it easier to deal with errors and fraud expected to arise when the system would be put into real operation.

Under these circumstances, the GPS input was now used to check the precision of the kilometer reading. During good GPS conditions, the OBU calculates odometer deviation on a daily and monthly basis, registering single irregularities as well as long-term deviation. Achievable precision lies in the range of 0.2 percent of the recorded distance. This is very helpful in detecting miscalibrated or disturbed odometer output and makes it nearly impossible for truck drivers or truck owners to manipulate the kilometer counting.

In the case of a complete lack of odometer input, the GPS with the help of the sensor system will detect the error and turn the OBU into a "red status." The OBU will then stop counting kilometers on its display. This will obviously lead to substantially different readings between the truck's tachometer

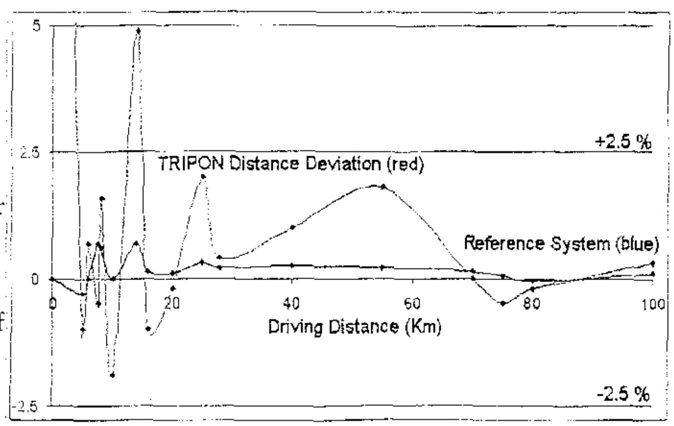


FIGURE 3 TripOn self-calibration. The error between the recorded driving distance (red line) and the calibrated distance recording with a laser reference system (blue line) gets smaller and smaller over distance due to the sensor system's self-learning algorithm.

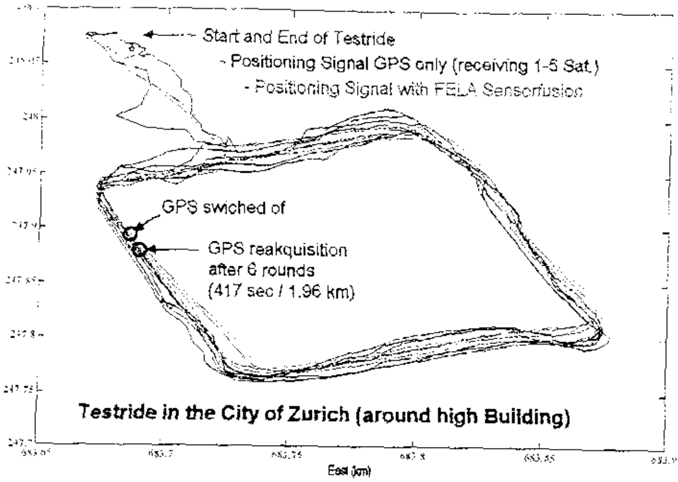


FIGURE 4 Test *drive in Zurich*

and the OBU reading. The red indicator LED tells the driver that the OBU is now no longer in an authorized mode, and that he should correct the error by visiting an approved LSVA workshop.

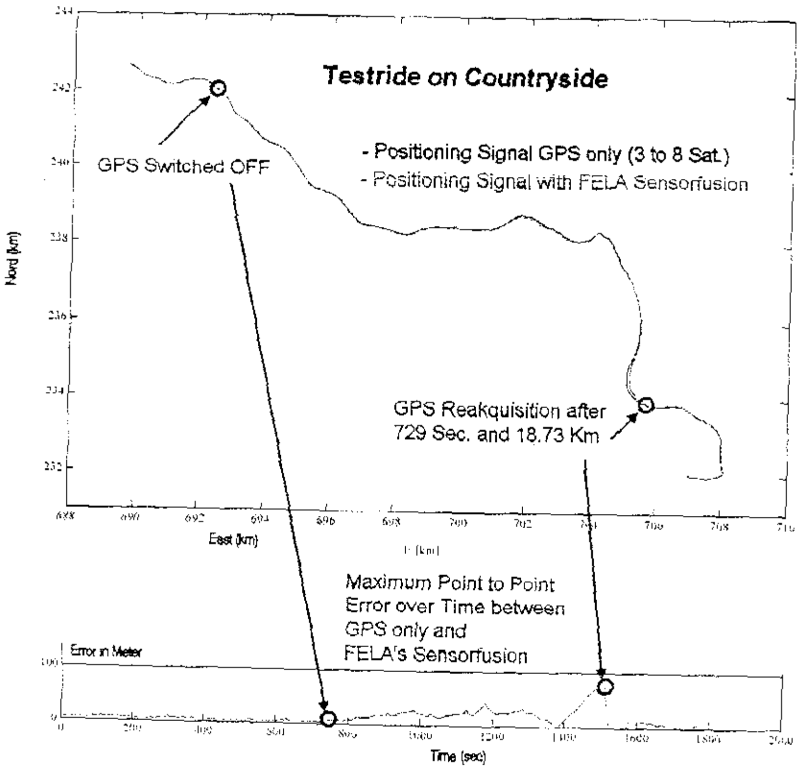
During this error condition, distance driven is recorded on the basis of GPS and sensor signals and stored in the log file for later evaluation by the taxation office.

Figures 4 and 5 show results of test drives with the GPS receiver turned off and on to simulate lack of availability.

Reviewing system development from the first ideas to the final implementation, odometer input, DSRC communications and manual declaration have finally been chosen by the OZD as the main input for collecting the Swiss heavy vehicle fee.

The GPS system component turned from being the main input device regarding the border crossing and distance counting functionality to a controlling and verification subsystem that helps overcome errors and fraud situations and also helps the driver make the proper declarations.

FIGURE 5 Test *drive in* countryside



Latest Developments

Let's also look into the future of new systems like motorway tolling in Germany and Austria and other planned European implementations. The German system in particular will be very interesting to watch as it will be the first to rely primarily on GPS for calculating motorway tolling fees and will use a GSM communication link to transfer the account balances from the onboard equipment into the central accounting system. The GSM link, or a more advanced GPRS connection, will also download new geodata or other parts of the OBU software.

There is no proven GPS-based tolling equipment on the market today, and operators face a challenge in handling all upcoming exceptions that will arise when dealing with 1.5 million installed units. Even very rare exceptions and errors will quickly multiply to a substantial number of problems.

To fulfill the new requirements of the upcoming systems, we have developed a new OBU EU, which will be interoperable with our existing units but will include all new software and our core technologies developed within our research and development department, such as:

- One of the smallest GPS module receivers on the market, developed to our specifications
- One of the smallest GSM modules for SMS and data, developed and manufactured to industrial standards by FELA, as the data link to the background system
- Fully programmable DSRC microwave modules covering all existing tolling applications based on the standardization work done by the European Committee for Standardization's Technical Committee 278, Road Transport and Traffic Telematics (CEN TC278).
- Software algorithms for better GPS performance, dead reckoning, interpolation, and map matching.

Key features. The new OBU provides:

- Full compatibility to the existing Swiss OBU, exchangeable within minutes
- no more restrictions to GPS areas, zones, and virtual gantries.
- Enhanced hardware based on the latest ARM7 32-bit architecture
- Enough memory to run several applications in parallel on a multitasking operating system
- Integrated GSM module for SMS and data communication
- Enhanced GPS dead reckoning based on odometer, gyro, and sensor inputs.

The software for enhanced GPS performance is particularly important. With GPS as the primary

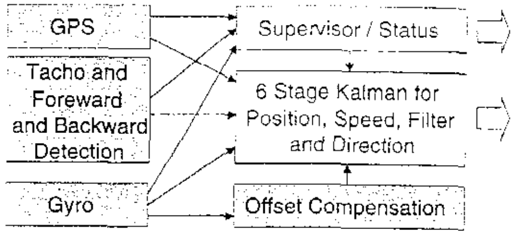


FIGURE 6 *Sensor fusion diagram*

data source, GPS startup and enhanced performance under bad conditions must be optimized. This includes optimization of GPS oscillator clock frequency for faster satellite tracking, download of newest almanac and ephemeris data after a longer off-mode period, optimized dead reckoning for position and driving distance update.

The new sensor fusion Shown in **Figure 6** produced dramatic improvements during short and longer losses of GPS signal. A highly optimized 6-stage Kalman filter combines GPS, gyro sensor, driving distance information, and offset compensation to get a high-quality position solution.

The OBU can now deliver precise position information for up to 10 minutes without GPS input, calculating position from tachopulses (distance) and vehicle turnrate (gyro). This makes it possible to track virtual gantries on motorways without the need for CD-ROMs for map-matching. (Virtual gantries are single points along a road that must be detected, but do not have roadside (DSRC) infrastructure. The data can be downloaded into the OBU, and when its GPS coordinates match the downloaded ones, the OBU may buzz or register a predetermined type of event.)

At Home and Abroad. Believe it or not, once you have gotten familiar with the visible LED light bars behind trucks' front windows while driving in Switzerland, you will miss them whenever you are on a foreign road.

Further information on the Swiss road tolling system for heavy vehicles can be found at: <www.afd.admin.ch/e/firmen/steuern/lsva/ausland.php>.

Manufacturers

The **Fela Management** (Diessendorf, Switzerland) *TRIPON* onboard unit, or OBU, uses the *TIM* GPS module from **u-blox** (Thalwil, Switzerland).

EC Proposes Satellite-Based Road Fees

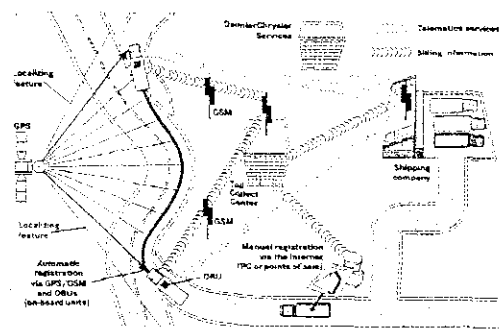
On April 23, the European Commission proposed to the European Parliament and European Council the implementation of a GNSS-based electronic toll collection system interoperable throughout all member states, to come online in 2008 — the same year that Galileo is scheduled to become fully operational.

If approved, the measure would accelerate adoption of GPS and Galileo functionality on hundreds of thousands, if not millions, of land vehicles. It would have a similar effect of stimulating follow-on market development, just as the E911 mandate in the United States has begun to drive GPS-enabling of cell phones.

"*Developing the trans-European transport network:* Innovative funding solutions and Interoperability of electronic toll collection systems" comes from the Directorate-General for Transport and Energy (DG-TREN) with preparatory work by the Research and Development Framework Programmes. Stating that the trans-European transport network is underfinanced, it advocates fee collection that "does not compromise traffic fluidity," equating this with interoperable toll systems across Europe, enabling a single subscription contract for intra-EU travel.

It advocates short- and medium-term solutions combining satellite positioning, mobile communications, and microwave technologies, but mandating a transition to the first two technologies exclusively from 2008 onward.

The 50-page proposal can be downloaded at <http://europa.eu.int/comm/transport/themes/network/doc/com_2003_0132_en.pdf>.



German Toll Collect

Germany plans to implement a $7.7-billion automatic road-tolling system for commercial truckers. The Toll Collect system uses GPS-equipped on-board units to measure truck movements along roads.

ETC.de, a consortium of DaimlerChrysler, Deutsche Telekom and French toll-road operator Cofiroute, will offer the service, scheduled to begin in 2003. Mandated for use by trucks of more than 12 tons, the system is expected to generate $3.4 billion per year.

Once a Toll Collect-equipped vehicle begins to move, the GPS receiver automatically identifies the road on which the vehicle is traveling. As soon as the truck enters a toll road, the onboard unit uses the truck's data (number of axles and emissions class) and the number of kilometers driven to calculate the tolls. A wireless communications link transmits the distances traveled by vehicles to the Toll Collect Center. The center then arranges payment of the toll with the shipping company. The positioning function of the navigation system reportedly is accurate enough to determine whether a truck is on a toll highway or a parallel toll-free road.