



Method for Determining the Distance of a Vehicle from a Radio Beacon and Radio Beacon for this Purpose

The present invention relates to a method for determining the distance of a
5 vehicle passing a radio beacon of a road toll system from this radio beacon, wherein the vehicle is equipped with an onboard unit, which emits a signal with a known curve of its frequency over time. The invention additionally relates to a radio beacon for implementing this method.

10 In radio beacon-based road toll systems, e.g. according to the DSRC (dedicated short-range communication) or WAVE (wireless access in a vehicle environment) standard, onboard units (OBUs) carried by the vehicles communicate with geographically distributed radio beacons as soon as they pass these. The radio communication generally serves to locate the vehicle on the radio coverage area of the
15 radio beacon in order to charge for usage of locations or also simply to transmit toll data generated by the OBU to radio beacons on its route.

It is often desirable to determine the distance at which the vehicle passes a radio beacon, e.g. to penalise toll violations in the case of multi-lane roads: when multiple
20 vehicles travelling next to one another on different lanes pass the radio beacon and one of its radio communications indicates a toll violation, e.g. a missed toll charge debit, an inadequate balance of a charge account, a defective or incorrectly adjusted OBU etc., or a lane-dependent charge rate or toll (multiple occupant lane) is to be calculated, then it is essential to know which of the vehicles travelling next to one another is responsible to



be able to identify this e.g. visually in situ or on an evidence photo of the road section of the beacon.

Various methods of determining the distance are known currently. One solution
5 is to use multiple physically offset receiving antennae in the radio beacon to determine the positions of the OBUs in the radio receiving field from phase difference measurements between the OBU signals received by the individual antennae. Another solution is known from the US patent 5,790,052 and is based on Doppler measurements of the different relative speeds of an OBU in relation to physically offset receiving
10 antennae of a radio beacon to determine the ratio of the distances from the two receiving antennae from the ratio of the speed measured values. Finally, it would also be possible to use a separate radio beacon with a low radio coverage range for each lane. All these known solutions are expensive, not least because they are based on multiple receiving antennae.

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The aim set by the invention is to provide a method for determining the distance of an OBU from a radio beacon in a road toll system, which requires lower equipment expenditure for conversion than the known solutions.

20 This aim is achieved in a first aspect of the invention with a method of the aforementioned type, which is distinguished by the steps:

receiving the signal in the radio beacon during passage of the vehicle and recording the curve of its frequency over time in relation to the known frequency curve;

detecting a change in the recorded frequency curve exceeding a predetermined threshold value;

looking for two far regions in the frequency curve lying before and after the detected change in time and which show a frequency change below a threshold value;

5 scaling the recorded frequency curve in such a manner that the far regions assume predetermined values; and

determining the said distance from the gradient of the scaled frequency curve in an inflection point thereof.

10 The invention makes use of the circumstance that at the time of direct passage the Doppler-related frequency change of the OBU signal is inversely proportional to the normal distance from the radio beacon, when the distance is minimal, so long as the frequency curve is normalised to the inherent speed of the vehicle. The latter is achieved by evaluating the frequency curve in "far regions": in these far regions the distance of
15 the vehicle compared to the normal distance is very large and this is negligible, and therefore the extent of the Doppler shift there depends substantially only on the inherent speed and this can be determined therefrom. Further, the dependence on the normal distance, and therefore this itself, can be determined from the analysis of the frequency curve compensated by the inherent speed in the near region of the beacon where the
20 greatest change ("Doppler jump") of the frequency pattern occurs in its inflection point. As a result, the passing distance can be determined from the radio communication between the OBU and the radio beacon alone with a single receiver and a single antenna.

The invention is suitable for onboard units with any type of known curves of their transmission frequency over time, whether they transmit a constant frequency, e.g. a constant carrier frequency, in which case the known frequency curve is simply "constant", or they transmit frequencies that vary in the frequency hopping process, the frequency change curve of which is known, so that the frequency curve received in the radio beacon can be normalised or referenced to the known transmission frequency curve.

The road lane of a multi-lane road on which the vehicle is moving is then preferably determined from the defined distance. As a result of this, toll violations in the case of parallel passing vehicles can be unequivocally associated with one lane and the vehicle or vehicles located therein.

According to a first advantageous embodiment of the invention the inflection point is determined by seeking the point in the frequency curve at which the frequency has a predetermined value, which is in particular the rated or resting frequency of the OBU. Therefore, this embodiment is suitable for those cases in which the rated frequency of the radio communication of the OBU is previously known.

According to an alternative preferred embodiment of the invention the inflection point is determined by seeking the point in the frequency curve at which the frequency corresponds to the frequency mean value of the far regions. The rated frequency of the OBU does not have to be previously known for this embodiment, the process adjusts automatically.

The Doppler shift evaluated with the method of the invention can be measured at any desired frequency of the signal, whether it is a carrier frequency or preferably a modulation frequency thereof. Modulation frequency is understood to be a frequency of any desired modulation of the OBU signal, whether it is a simple frequency or amplitude modulation, one of the modulation frequencies of an OFDM modulation, or also a pulse or burst modulation such as occurs as a result of periodic transfers of entire data blocks; such a block repetition rate can also be regarded as a modulation frequency, the Doppler frequency shift of which can be measured.

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The method of the invention is suitable for all types of radio beacon-based road toll systems. The method is particularly suitable for DSRC and WAVE road toll systems, in which a DSRC or WAVE transmitter of the onboard unit is used to emit the signal. Other configurations using RFID technology, or also any cellular (e.g. GSM, UMTS, LTE) and near-range radio technologies (e.g. Bluetooth, WLAN), are also possible.

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In a further aspect the invention also provides a radio beacon for a road toll system for determining the distance of a vehicle passing this, which is equipped with an onboard unit, which emits a signal with a known curve of its frequency over time, said radio beacon being distinguished by:

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a receiver, which is configured to receive the signal of a passing vehicle;

a memory connected to the receiver, which is configured to record the curve of the frequency of the received signal over time in relation to the known frequency curve over time;

5 a detector, which is connected to the memory and is configured to detect a change in the recorded frequency curve;

an evaluation device, which is connected to the detector and the memory and is configured to look for two far regions in the frequency curve lying before and after the detected change in time and which show a frequency change below a threshold value;

10 a scaling device, which is connected to the memory and the evaluation device and is configured to scale the recorded frequency curve in such a manner that the far regions assume predetermined values; and

a differentiator connected after the scaling device, which determines the gradient of the scaled frequency curve in an inflection point thereof and determines the distance therefrom.

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The radio beacon is preferably installed on a multi-lane road and the differentiator is configured to determine the lane, on which the vehicle is passing, from the distance.

20 In a first embodiment the differentiator determines the inflection point by seeking the point in the frequency curve, at which the frequency has a predetermined value.

Alternatively, the differentiator determines the inflection point by seeking the point in the frequency curve, at which the frequency corresponds to the frequency mean value of the far regions.

5 In any case, the received signal can be modulated with a modulation frequency and the said frequency can be the modulation frequency, which is obtained in the receiver by demodulation.

The receiver is preferably a DSRC or WAVE transmitter.

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With respect to the advantages of the radio beacon according to the invention, reference is made to the above embodiments for the method.

The invention shall be explained in more detail below on the basis of preferred
15 exemplary embodiments with reference to the accompanying drawings:

Figure 1 is a schematic plan view of a radio beacon on a multi-lane road showing the geometric relationships during the passage of two vehicles;

20 Figure 2 shows frequency curves of the signals of two vehicles when passing the radio beacon;

Figure 3 shows the frequency curves of Figure 2 after being scaled;

Figure 4 shows the differentials of the scaled frequency curves of Figure 3; and

Figure 5 is a block diagram of the radio beacon of the invention.

Figure 1 shows a road toll system 1 comprising a plurality of geographically distributed radio beacons 2 (only one shown for representation), which connect with a central control unit (not shown) of the road toll system 1 via data connections 3. The radio beacons 2 are respectively installed on a road 4 that can comprise multiple carriageways or lanes 5, 6.

For example, the radio beacon 2 consists of a local computer 7, a (transceiver/) receiver 8 and a camera 9, which - operated by the computer 7 - can record images of the road 4 with its lanes 5, 6 for penalising toll violations.

The (transceiver/) receiver 8 serves to conduct radio communications 10 with onboard units or OBUs 11 carried by vehicles 12 passing the radio beacon 2 in the lanes 5, 6. The radio communications 10 are generally bidirectional data package connections. An analysis of the signals sent by the OBUs 11 to the (transceiver/) receiver 8 of the radio beacon 2 is sufficient for the purposes of the present invention, and therefore the following will only describe the OBU 11 sending signals 10 to the receiver 8 of the radio beacon 2. However, it is understood that in practice signals are also sent in the opposite direction.

The vehicles 12 with the OBUs 11 travel in lanes 5, 6 at different speeds v_1, v_2 past the radio beacon 2, more precisely its receiver 8, at different passing or normal distances a_1, a_2 . In this case, the signals 10 emitted by the OBUs 11 are respectively subject to frequency-dependent Doppler shifts in accordance with the known formula

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$$f_D = \frac{f_s}{1 - \frac{v}{c}} \quad (1)$$

where

f_s - transmission frequency of the signal 10 of the OBU 11

10 f_D - Doppler-shifted receiving frequency of the signal 10 in the radio beacon

2 if the OBU 11 were to move towards it front on;

v - speed of the OBU 11; and

c - speed of light.

15 If the OBU 11 travels past the distance 2 at a distance a , equation (1) can be written by means of geometric deliberations as

$$f_B \equiv \cos \left[\arctan \left(\frac{a}{x} \right) \right] f_D \quad (2)$$

20 where

a - vertical distance of the OBU 11 from the radio beacon 2 in the coordinate system of Figure 1;

x - horizontal distance of the OBU 11 from the radio beacon 2 in the coordinate system of Figure 1; assuming a constant speed v or v_1, v_2 of the OBUs 11 the horizontal distance also simultaneously corresponds to time t ; and
 f_B - Doppler-shifted receiving frequency of the signal 10 in the radio beacon 2 when the OBU 11 is moving past it at the distance a .

Figure 2 shows two exemplary curves of the receiving frequency f_B in relation to the horizontal distance x or the time t . The solid line 13 shows the receiving frequency curve for the OBU 11 in lane 5 and the broken line 14 shows that for the OBU 11 in lane 6. As can be seen, the Doppler-related frequency shift $\pm\Delta f_1, \pm\Delta f_2$ in "far regions" 15, 16 of the frequency curves 13, 14 far before and after a region 17 of maximum change $f_B' = \partial f_B / \partial t$ is small, i.e. the frequency change f_B' lies below a significance threshold ϵ in the far regions 15, 16.

Therefore, in the far regions 15, 16 (and naturally also further outside these) the extent of the Doppler shift $\pm\Delta f$ is scarcely dependent on the passing distance a any longer and instead is almost exclusively dependent on the speed v . The effect of the vehicle speed v on the frequency curves 13, 14 can therefore be eliminated by scaling these so that they respectively assume the same value in the far regions 15, 16, e.g. a predetermined value $\pm\Delta F$.

Figure 3 shows the result of such scaling, in which the indicated frequency curves 13, 14 have been scaled ("normalised") so that they assume the predetermined values $\pm\Delta F$ in the far regions 15, 16.

5 The scaled frequency curves 13', 14' therefore are more dependent on the ratio a/x , i.e. the passing distance a to the horizontal distance x or to the time t , in accordance with the following

$$f_B \equiv \cos \left[\arctan \left(\frac{a}{x} \right) \right] f_s \quad (3)$$

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As may be seen from Figure 3, the scaled frequency curves 13', 14' differ particularly clearly in their gradient $f_B' = \partial F_B / \partial t$ at the location $x = t = 0$, at which their curve at the same time shows an inflection point 20: the greater the passing distance a , the "more abraded" the scaled frequency curve 13', 14', i.e. the lower the gradient f_B' at the inflection point 20. Therefore, the passing distance a is inversely proportional to the

15 gradient f_B' , i.e.

$$\frac{1}{a} \equiv \lim_{x \rightarrow 0} f_B'(x) \quad (4)$$

20 The gradient f_B' at the inflection point 20 can be determined by differentiating the scaled frequency curves 13', 14', and the result of the differentiation is shown in Figure 4.

With knowledge of the lane width b_1 , b_2 of lanes 5, 6 - the respective lane 5, 6 in which the OBU 11 was located during the transmission of its signal 10 can then be determined from the passing distances a_1 , a_2 determined in this manner. A simple relative comparison of the passing distances a_1 , a_2 is often also sufficient to determine the local
 5 sequence of the vehicles.

It has been assumed hitherto that the transmitting frequency f_s of the signal 10 of the OBU 11 is constant, i.e. its own frequency curve is a constant curve. However, it is also possible that the OBU 11 transmits a signal 10 with a transmitting frequency curve
 10 that is non-constant in time, e.g. in the case of frequency hopping radio communications, in which the transmitting frequency f_s constantly changes - according to a predetermined or known pattern. The recorded receiving frequency curves 13, 14 are recorded relative to the prior known curve of the transmitting frequency f_s over time of the OBU 11, whether it is constant or changing, i.e. is referenced or normalised to
 15 these, so that the effect of known changes in transmitting frequency of the OBU 11 can be compensated.

Therefore, in summary, the method for determining the passing distance a of the OBUs 11 passing the radio beacon 2 is configured as follows:

20 Firstly, the frequency curve 13, 14 of the signal 10 of the OBU 11 is plotted in relation to time t ($= x$) - possibly based relatively on a prior known curve of the transmitting frequency f_s over time. Then, the region 17 is approximately determined in the frequency curve 13, 14 at which a significant change indeed occurs, i.e. $\partial f_B / \partial t$ exceeds a predetermined detection threshold s . This serves to obtain a time reference

point for seeking the two far regions 15, 16 which must lie before and after the change 17 and be so far removed from this that no further significant frequency change $\partial f_B / \partial t$ occurs in these, i.e. this lies below a predetermined significance threshold ϵ .

5 With knowledge of the far regions 17, 18 and the Doppler shifts $\pm \Delta f_1, \pm \Delta f_2$ occurring therein (which can also be considered to be quasi-constant because their change does not exceed the significance threshold ϵ), the frequency curves 13, 14 can now be scaled so that they respectively assume the same predetermined value $\pm \Delta F$ in their far regions 15, 16.

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The inflection point 20 is then sought in the scaled frequency curves 13', 14'. For this, the location x or the time t is sought in the frequency curves at which the receiving frequency f_B assumes either the frequency mean value (the "middle") between the "quasi-constant" far regions 15, 16 or - if the rated frequency of the signal 10 of the
15 resting OBU 11 is known - assumes this rated frequency. The inflection point 20 can be determined in both ways, i.e. both before the scaling in the frequency curves 13, 14 and after the scaling in the scaled frequency curves 13', 14'.

20 After determining the inflection point 20, the gradient $f_B' (x=t=0)$ of the scaled frequency curves 13', 14' in the inflection point 20 can now be determined (see Figure 4) and the passing distance a or a_1, a_2 can be determined therefrom, as explained above.

Figure 5 shows an exemplary hardware configuration of the radio beacon 2 for conducting the outlined method. Connecting to the receiver 8 the radio beacon 2 has a

memory 21, in which the time frequency curves 13, 14 of the received signals 10 are recorded. A detector 22 connected to the memory 21 detects the change region 17 ($\partial f_B / \partial t > s$) and feeds this information 17 to an evaluation device 23. The evaluation device 23 determines the far regions 15, 16 of the frequency curves 13, 14 with $\partial f_B / \partial t <$
 5 e therefrom and with this information 15, 16 actuates a scaling device 24 that scales the frequency curves 13, 14 to scaled frequency curves 13', 14'. The latter are fed to a differentiator 25, which calculates the gradient $f_B'(0) = \partial f_B / \partial t$ at the location $x = t = 0$ of its inflection point 20 in order to determine the passing distances a_1, a_2 therefrom.

10 The components 21 - 25 can be implemented, for example, by the local computer 8 of the radio beacon 2.

The invention is not restricted to the represented embodiments, but covers all variants and modifications that fall within the framework of the attached claims.

Patent Claims:

1. Method for determining the distance of a vehicle passing a radio beacon of a road toll system from this radio beacon, wherein the vehicle is equipped with an onboard unit, which emits a signal with a known curve of its frequency over time, characterised by the steps:

receiving the signal in the radio beacon during passage of the vehicle and recording the curve of its frequency over time in relation to the known frequency curve;

detecting a change in the recorded frequency curve exceeding a predetermined threshold value;

looking for two far regions in the frequency curve lying before and after the detected change in time and which show a frequency change below a threshold value;

scaling the recorded frequency curve in such a manner that the far regions assume predetermined values; and

determining the said distance from the gradient of the scaled frequency curve in an inflection point thereof.

2. Method according to claim 1, characterised in that the lane of a multi-lane road, on which the vehicle is moving, is determined from the distance.

3. Method according to claim 1 or 2, characterised in that the inflection point is determined by seeking the point in the frequency curve, at which the frequency has a predetermined value.
- 5 4. Method according to claim 1 or 2, characterised in that the inflection point is determined by seeking the point in the frequency curve, at which the frequency corresponds to the frequency mean value of the far regions.
- 10 5. Method according to one of claims 1 to 4, characterised in that the signal is emitted by the onboard unit as at least one carrier frequency modulated with a modulation frequency, wherein the said frequency is the modulation frequency.
6. Method according to one of claims 1 to 4, characterised in that a DSRC or WAVE transmitter of the onboard unit is used to emit the signal.
- 15 7. Radio beacon for a road toll system for determining the distance of a vehicle passing the radio beacon, which vehicle is equipped with an onboard unit which emits a signal with a known curve of its frequency over time, characterised by:
 - a receiver, which is configured to receive the signal of a passing vehicle;
 - 20 a memory connected to the receiver, which is configured to record the curve of the frequency of the received signal over time in relation to the known frequency curve over time;
 - a detector, which is connected to the memory and is configured to detect a change in the recorded frequency curve;

an evaluation device, which is connected to the detector and the memory and is configured to look for two far regions in the frequency curve lying before and after the detected change in time and which show a frequency change below a threshold value;

5 a scaling device, which is connected to the memory and the evaluation device and is configured to scale the recorded frequency curve in such a manner that the far regions assume predetermined values; and

 a differentiator connected after the scaling device, which determines the gradient of the scaled frequency curve in an inflection point thereof and
10 determines the distance therefrom.

8. Radio beacon according to claim 7, characterised in that it is installed on a multi-lane road and the differentiator is configured to determine the lane, on which the vehicle is passing, from the distance.

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9. Radio beacon according to claim 7 or 8, characterised in that the differentiator determines the inflection point by seeking the point in the frequency curve, at which the frequency has a predetermined value in the frequency curve.

20 10. Radio beacon according to claim 7 or 8, characterised in that the differentiator determines the inflection point by seeking the point in the frequency curve, at which the frequency corresponds to the frequency mean value of the far regions.

11. Radio beacon according to one of claims 7 to 10, characterised in that the received signal has at least one carrier frequency modulated with a modulation frequency, and the said frequency is the modulation frequency, which is obtained in the receiver by demodulation.

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12. Radio beacon according to one of claims 7 to 11, characterised in that the receiver is a DSRC or WAVE transmitter.