1 Introduction

The Kinetis Wheel Location (KWL) software module was developed by NXP using the Kinetis Design Studio Integrated Development Environment (IDE) and the NXP FRDM-SENSORS-LF board assembly. This document presents the main concepts behind the wheel location algorithm of the KWL software. The document details the approach used and explains how this led to the current implementation. The purpose of the wheel location algorithm is to locate the four Tire Pressure Monitoring System (TPMS) sensor modules (tags) placed in the wheels.

- front left wheel
- rear left wheel
- front right wheel
- rear right wheel

Each tag is recognized by its unique identification number (ID). When the algorithm starts, the ID of each tag is known, but its position is not. The system does not know which sensor is in which wheel. Once the algorithm has converged, each tag ID is linked to a position in the car. The position of the tag is determined by two values:

- the side of the car (left or right)
- the position on a given side of the car (front or rear)

In the NXP approach, the side of the car value is determined based on the rotation direction of the wheels. Then, using a value for the position of the wheel on the car (front or rear), a determination is made to identify the front wheels from the rear wheels, based on the rotation periods of the wheels during a turn. This method and its advantages are detailed throughout this document.

2 Configuration of the car

The vehicle is assumed to have two steered wheels (front) and two trailing wheels (rear). The four wheel diameters are presumed to be the same. Otherwise, comparing wheel rotation periods would lead to incorrect conclusions, since the rotation period is directly proportional to the wheel diameter. The pressure in all four tires must be verified before running the wheel location algorithm, often occurring when the TPMS sensor modules are detected.
3 Physics of the car

3.1 Wheel direction of rotation – distinguishing between left and right sides

The TPMS tags are always mounted the same way in each wheel of the car. The sensors on the left side and the sensors on the right side are mounted such that they both face outward from the wheel. The TPMS accelerometers detect opposite directions of rotation (+X-axis versus –X-axis), as a result. See Figure 1.

![Figure 1. Determining side of car through direction of wheel rotation](image)

When travelling forward, the left wheels rotate counter-clockwise and the right wheels travel clockwise. The determination method is the opposite when the car is traveling backward, since the left wheels rotate clockwise and the right wheels rotate counter-clockwise.

Within the first few rotations of the wheel, the software computes the wheel’s rotational direction. In the algorithm flow, once the direction of the car is known, either forward or backward, and the rotation direction of the tags in the wheels is known, the tags can be located on the correct side of the car. This is a fast and reliable way to distinguish the left side from the right side of the car. Calculating the rotation direction of the wheel requires a 2-axis accelerometer, which is why dual-axes devices are necessary to run this algorithm. The determination between front and rear wheel positions is yet to be accomplished.

For more information on the wheel location software function, refer to the KWL-TPMS Wheel Location Module Reference Manual (NXP document ID TPMSWHEELOCMODRM)

4 Calculating rotational periods

4.1 Distance traveled by four wheels

When the car is turning, the four wheels travel different distances during the same amount of time. Therefore, they have different speeds. If a wheel has a longer path to travel than another wheel, the former rotates faster and has a smaller rotation period than the latter. See Figure 2.
Why four wheels travel at different distances?

The difference in distance between the wheels in a turn is due to the fact that the four wheels each have different turning radii, when the car is turning. See Figure 3.

Notice first that in a left turn (see Figure 3), the right wheels have a larger turning radius than the left wheels because the two sides are separated by the distance, W. Distance W is called the track and represents the distance between the left side and the right side, from the center of a wheel to the center of the opposite wheel. In the case of a right turn, it is reversed. The left wheels have a larger turning radius than the right wheels.
On a given side, the difference in the distance travelled between the front and rear wheels is less obvious. The front wheels have a larger turning radius than the rear wheels and thus travel a greater distance than the rear wheels do during a turn. This is due to the fact that the front wheels are the steered wheels and the rear wheels are the trailing wheels. The orientation of the front wheels is changed (pivoted) as the car is steered. The front wheels are no longer parallel to the car, they typically pivot from the direction of travel of the vehicle by 0 to 40 degrees.

The rear wheels cannot follow the same path as the front wheels. The rear wheels always point towards the front wheels. During a turn, the path of the rear wheels is inside the tracks of the front wheels. Figure 4 shows the path of the four wheels, the yellow arrows represent the direction of the rear wheels during the left turn. The rear wheel paths are shorter than the paths of the front wheels and their turning radius is shorter.

Figure 4. Wheel travel paths, front and rear in a left turn

Analyzing travel path of four wheels

Figure 5 illustrates a vehicle left turn and the increasing rotation period or the decrease in the turning radius, resulting in different travel distances of each wheel.
In a left turn, the inner side is the left side and the outer side is the right side.
In a right turn, the inner side is the right side and the outer side is the left side.

Figure 5. Left turn, longest and shortest travel paths

The differences in rotational periods between the four wheels are as follows:

- Outer front wheel has the smallest rotational period
- Outer rear wheel has a slightly larger rotational period
- Inner front wheel has a still larger rotational period
- Inner rear wheel has the largest rotational period

The function of the wheel location algorithm is to locate the four wheels by comparing their rotation periods. Each TPMS tag assists in the calculation of the rotation period of the wheel in which it is placed, by its contributing accelerometer data. The sensor transmits the rotation period to the RF receiver module, which stores the rotation periods sent by the four TPMS tags and compares them. This concept is described with more detail in the next section.

In order for this method to work, the difference between the rotation periods of the four wheels must be large enough to be detected. If the rotation periods of the four wheels differ only by a few milliseconds, this difference is of the same order of magnitude as the
imprecision in the calculation of the rotation period. The imprecision is due to the level of noise in the wheel. The resulting comparison is not reliable and not useful in determining for certain, which wheel has the largest or shortest rotation period. On the contrary, if the difference between the rotation periods is high, as in several dozens of milliseconds, then it is easy to differentiate the four wheels, and the results of the comparison are reliable. In summary, the bigger the difference between the rotation periods, the easier it is to differentiate the four wheels. In the next section, the relationship between traveled path and rotation period is discussed.

4.2 Relationship between traveled path to rotation period

The rotation period is the time required by a wheel to execute a complete rotation. This is the time during which the wheel travels a distance equal to its circumference (circumference = $2\pi \times \text{wheel radius}$).

The following equation applies:

$$\text{rotation period} = \frac{2\pi \times \text{wheel radius}}{\text{speed of the wheel}}$$

- At a given speed, as the circumference of a wheel increases, the rotation period of the wheel also increases. If the wheel circumference is larger, the wheel needs more time to execute a rotation.
- For a given wheel radius, the higher the speed, the shorter the rotation period. If the speed is higher, the wheel executes a rotation in less time.

These two parameters have an influence on the absolute value of the rotation period, but not on the relative difference between the rotation periods of the four wheels during a turn.

Showing the influence of speed on rotational period

- The car is turning left with a steering angle of 20 degrees, the inner front wheel pivots at 20 degrees. The wheel radius is 24 cm.
- The first scenario—the car is travelling at 40 km/h
- The second scenario—the car is travelling at 10 km/h

In the first scenario, the rotation periods of the four wheels are the following:

- Right front wheel: 125 ms
- Right rear wheel: 130.5 ms
- Left front wheel: 148 ms
- Left rear wheel: 157.5 ms

The difference between the two right wheels is 5.5 ms. This represents 4.4 % of the period of the right front wheel.

The difference between the two left wheels is 9.5 ms. This represents 6.4 % of the period of the left front wheel.

$$\frac{5.5 \text{ ms}}{9.5 \text{ ms}} = 57.9 \%$$
In the second scenario, the rotation periods of the four wheels are the following:

- Right front wheel: 500 ms
- Right rear wheel: 522 ms
- Left front wheel: 592 ms
- Left rear wheel: 630 ms

The difference between the two right wheels is 22 ms. This represents 4.4% of the period of the right front wheel, which is the same percentage as in scenario 1.

The difference between the two left wheels is 38 ms. This represents 6.4% of the period of the left front wheel, which is the same percentage as in scenario 1.

\[
\frac{22 \text{ ms}}{38 \text{ ms}} = 57.9 \%
\]

From this example, decreasing the speed increases the four rotation periods, but does not enhance the relative difference between them. Increasing the wheel radius leads to the same conclusion.

In the algorithm, is vehicle speed a necessary consideration? Yes, because it is easier and more reliable to compare high numbers than low numbers as the data are further from the noise level. It is easier to see a difference in rotational periods of 22 ms (the second scenario) than a difference of 5.5 ms, which is close to the imprecision due to the noise (the first scenario). In this example, differentiating the wheels is more reliable at 10 km/h than at 40 km/h. This is why the algorithm is meant to be used only at low speeds, from approximately 3 km/h to 30 km/h. It is easier to differentiate wheels with a large radius, since increasing the wheel radius increases the rotation period. If the wheel radius is small, then the rotation periods are short and the difference between them is close to noise level.

In conclusion, the two parameters, speed and wheel radius, have an influence on the absolute values of the rotation periods, but they do not enhance the relative difference between the rotation periods.

### 4.3 Parameters enhancing difference between rotation periods

There are two parameters that have an influence on the relative difference between the rotation periods.

- steering angle (variable)
- ratio of track to wheelbase (fixed)

The parameter with the most influence on rotation periods is the steering angle, the angle with which the front wheels pivot during a turn, since it is controllable.
4.3.1 Steering angle affecting rotational periods of four wheels

Figure 6 shows that as the steering angle increases, the difference between the rotation periods of the four wheels also increases. The difference between the rotation periods of the two wheels on the same side, is called the margin. Increasing the steering angle affects the rotational period in two ways:

- Increase in both left-side and right-side margins.
- Increase in the difference between the left-side and the right-side rotational periods.

In the TPMS wheel location GUI, this margin is displayed as left-side and right-side confidence indicators. For a description of the TPMS wheel location software Graphical User Interface (GUI), see NXP document ID TPMSWHEELLOCGUIUG.

![Figure 6. Rotation periods of four wheels in left turn at 10 km/h with different steering angles](image)

Differentiating the left side from the right side is not a problem, given access to the information on the direction of rotation. Even if rotation periods only are used, the difference between the two sides is always large, even at small steering angles. But there is still the task to differentiate the front wheels from the rear wheels. This is easier and more reliable if the margins of both sides are large, in the order of several dozens of milliseconds. It is easier to differentiate the wheels when the steering angle increases. This is why, in the algorithm, the rotation periods of the four wheels are compared, but only if the steering angle is beyond a threshold. Typically this threshold is around 10 degrees. Above that, the margins are high enough to be able to differentiate the front wheels from the rear wheels. Below this threshold, the margins are only around a few milliseconds, which is too close to the level of noise.
4.3.2 Ratio of car width to length affecting rotational periods of four wheels

The other parameter with a less significant influence on wheel rotation periods is the ratio

\[
\frac{\text{track}}{\text{wheelbase}} = \frac{W}{L}
\]

Typically for cars, this ratio is around 0.57, Width = Length × 0.57.

The graph in Figure 7 shows that, at a fixed length L, when the width, W, increases, the difference between the left side and the right side is enhanced. This makes sense given that the difference of the turning radius between the left and right side is determined by the width of the car. For larger/wider cars, with an assumed fixed length, the difference between the left side and the right side rotational periods is bigger.

Regarding the impact of this ratio, it can be seen that the ratio has little influence, considering standard sizes of cars. For a ratio of W/L = 0.52, the difference between the left front wheel (green curve) and the right rear wheel (blue curve) is 60 ms. However, for cars with a ratio of 0.61, this difference increases to 80 ms. Therefore, the ratio modified this difference by only 20 ms. This parameter has no influence on the difference in rotational periods between the two wheels on the same side. The curves representing the wheels on a same side appear to be parallel. In fact, there is a small difference between the curves so they are not truly parallel, but the difference is negligible.

Having discussed the parameters that have an influence on the rotation period of the wheels, the method used to compare these rotation periods is discussed in the next section.
5 Comparing rotation periods and estimating reliability

When the car is going at low speed, between 3 km/h and 30 km/h, TPMS tags send their data by RF signals to the RF receiver and the algorithm continuously calculates the rotation periods, as well as the information on the rotation directions. For more details on wheel rotational speed comparisons, refer to the TPMS wheel location project reference manual (NXP document ID TPMSWHEELLOCPRJRM).

5.1 Comparing rotation periods

For a given car, the speed and the steering angle have an influence on the value of the rotation periods of the four wheels. This implies that, to determine two rotation periods from two different wheels and compare them, these rotation periods must have been calculated under the same conditions, at the same speed and with the same steering angle.

If the rotation period of the first wheel has been calculated when the car is going 10 km/h with a steering angle of 20 degrees and the rotation period of the second wheel is 30 km/h with a steering angle of 30 degrees, then comparing the two rotation periods is not relevant.

To compare one-by-one the rotation periods of the four wheels, this requires collecting data that has been calculated under the same conditions. This is constraining, since speed and steering angle are not constant during a turn; they can even change rapidly.

The information sent by the TPMS tags can be lost because RF communication is not 100% reliable. As a result, this method is not used in the algorithm. Instead of comparing the rotation periods one-by-one, TPMS collects all the rotation periods received from the four TPMS tags during a turn.

At the end of the turn, all the rotation periods received from each sensor module during the whole turn, are stored. Then, for each tag the average of the rotation periods received is calculated and the result is four, averaged rotation period values. These averaged values are compared to differentiate between the four wheels. The highest averaged value is deduced to be from the inner rear wheel and the lowest averaged value from the outer front wheel.

The longer the turn, the more data is received and the more reliable the final result. When data is collected throughout the turn, the data collected is more representative of the turn. If, for one or more wheels, a minimum number of data packets is not received by the TPMS, currently this is three sets of data, then the comparison is not performed. This is to ensure that enough samples are available for each wheel to make certain the averaged value is representative of the whole turn. Refer to Section 6 “Algorithm flow - summary and example” for more information.

5.2 Estimating reliability of comparison wheel rotation periods

The results of a comparison between the rotation periods of the four wheels, that is the averaged values of their rotation periods, is more reliable when the margins on both sides are higher. By comparing the margins, the difference between the rotation periods of the two slowest wheels, those with higher rotation periods, and the two fastest wheels, those with the lowest rotation periods, are evaluated. Figure 8 shows another example illustrating the margins.
Figure 8 shows the evolution of the rotational periods of the four wheels during a particular maneuver. At first, the car is going straight and the four wheels have the same rotation period, around 270 ms. Then, the vehicle starts turning left as the driver progressively increases the steering angle. When the turn is almost completed, after around 3.5 seconds, the driver starts decreasing the steering angle so that the car goes straight again.

From the graph, the margins reach a maximum when the steering angle is at the maximum, just before the driver starts decreasing the steering angle to go straight again. The margins showed in this graph correspond to the difference between two rotation periods at a given moment.

In the algorithm, the margins for each side are calculated, but instead of performing the calculation between two rotation periods, they are performed on the averaged rotation periods.

For example, at the end of the turn the slowest wheel, the one with the highest averaged rotation period, which in this example corresponds to the left rear wheel, has an averaged rotation period of 300 ms. The average of the rotation periods of the second slowest wheel, the left front wheel is 290 ms. Therefore, the margin of the slowest side, the left side, for this turn is equal to 10.

Once the vehicle finishes the turn and calculates the two margins, for both sides, the slowest and the fastest, the values of the two margins are stored until the next turn, in order to sum them with the margins of the next turn. The margins are accumulated from one turn to the next, as long as the algorithm is running.

Assume the left side average margin of the first turn is 10 while the left side average margin of the second turn is 20. By accumulating both averages at the end of the second turn, the updated total left side margin is $10 + 20 = 30$. Then, if the left side margin of the third turn is 20 again, the resulting total left margin is updated to 50. This gives an indicator on the reliability of the comparison between the averaged rotation periods. If the accumulated margins are high after one or several turns, it means the tire location is reliable. On the contrary, if the margins are close to zero, then the location result is not reliable. These margins are meant to
be used as indicators to stop the algorithm, provided that both margins are below a given threshold. To determine this, the algorithm progresses and the total margins are updated at the end of each turn. When the margins go above the threshold, the reliability parameter is reached. Therefore, the algorithm can be stopped and the current tire location is considered as the final, reliable tire location. In the TPMS wheel location GUI, the margin threshold is set during software configuration by means of the Confidence Margin slide control.

6 Algorithm flow - summary and example

Figure 9 is a summary of the algorithm flow as implemented in the RF receiver module.

Figure 9. Wheel location algorithm flow

To illustrate the calculations performed to locate the tags and update their locations and margins, consider Figure 10 and the example that follows.
The margin threshold, as mentioned in the previous section is set to 50. The wheels on the outer side of the vehicle go faster than the ones on the inner side. On a given side, the rear wheels have a larger rotation period than the front wheels of the same side.

In this example, only two TPMS tags, labelled as AA and BB, are referenced for simplification, but the same method is used for the other two wheels.

- The first turn is left, this information is acquired from a gyroscope or directly from the car, if access to a data bus is possible. The car is progressing forward, information either from a low-g accelerometer or that reported from the car, informs the TPMS of the vehicle's direction of movement. At the end of the turn, the highest averaged rotation period is 255 ms for BB and the second highest averaged rotation period is 250 ms for AA. TPMS deduces that AA and BB are on the same side and verifies that by looking at their rotational directions. They both rotate counter-clockwise so they are indeed on the same side, which is the left side of the car. The rotation period of BB is higher than that of AA, therefore AA is deduced to be the front wheel.
and BB is the rear wheel with a margin of 5 (255 – 250 = 5). The reliability parameter has not yet been reached and the algorithm continues to run because 5 is below the margin threshold.

- At the end of the second turn, which is again a left turn and the vehicle is still moving forward, the highest averaged rotation period is 300 ms for AA and the second highest averaged rotation period is 275 ms for BB. From the information of this turn, the rotation period of AA is higher than the rotation period of BB so AA is now deduced to be the rear wheel and BB is the front wheel with a margin of 25 (300 – 275 = 25). Next, this data is compared with the previous results from the first turn. Previously the TPMS concluded a margin between the wheels to be 5. As 5 is lower than 25, the location from the second turn is considered to be more reliable. By updating the total margin, and taking into account that there were contradictory results between the two turns, the margin is now 20, (25 – 5 = 20). The location for AA is the rear wheel and BB is the front wheel, with a margin of 20. The value 20 is below the margin threshold and the algorithm continues to run.

- At the end of the third turn, which is a right turn and the vehicle is still moving forward, the lowest averaged rotation period is 260 ms for BB and the second lowest averaged rotation period is 300 ms for AA. In this turn, AA is higher than BB and TPMS decides that AA is the rear wheel and BB is the front wheel with a margin of 40. When compared with the previous results; AA is confirmed as the rear wheel and BB as the front wheel with a margin of 20 (20 + 40 = 60). With 60 being above the margin threshold, the algorithm stops and the current location is reliable; AA is the left rear wheel and BB is the left front wheel.

For additional information about the TPMS software algorithms, refer to the TPMS algorithm reference manual (NXP document ID TPMSWHEELLOCALGORM).
7 Revision history

Table 1. Revision history

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<tr>
<td>AN5322 v.1.0</td>
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<td>initial release</td>
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8 Contact information

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