Specifics of Bending Priority Road at Unsignalized Intersections

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Abstract. Unsignalized intersections with a bending priority road are common in Slovakia’s road network. Various specifics are associated with these type of intersections compared to conventional intersections with a straight priority road. There are different priority ranks for traffic streams, more complicated traffic situation, different traffic flow characteristics and driver behaviour. The problem is that only a few studies to date have addressed to this type of intersections and their specifics. Therefore, some traffic flow characteristics such as the speed of major-stream vehicles; and driver behaviour such as compliance with traffic rules, influences of potentially conflicting traffic streams on minor-stream drivers, and the driver gap-acceptance characteristics (critical gaps) at unsignalized four-leg intersection with a bending priority road in Žilina were surveyed. The results show vehicles moving along the bending major street about 40% slower than the city speed limit of 50 kilometres per hour. About 16% to 25% of drivers turning right from the major street did not signal the change of direction. About 16% of priority rule violations were recorded at the least priority minor approach during peak hours and long delays. There are two times more potentially conflicting traffic streams compared to intersection with the straight priority road and the effect of these potentially conflicting streams has ranged between 20% and 60%. The paper demonstrate that the values of critical gaps for the same movements more significant differ according to major/minor street and rank of priority, and critical gap values for straight traffic streams of third and fourth priority rank were determined to be about 0.4 to 0.9 second higher in comparison to the values for conventional rural unsignalized intersections. This new findings cause reduction of minor stream potential capacity and traffic safety.

1. Introduction
At unsignalized intersections, a “bending” priority road is a case where the major street is not straight, but there is a bend. Various specifics are associated with these intersections compared to when the priority road runs straight. Their specific mode of right-of-way results in different priority ranks of traffic streams, more complicated traffic situation, different traffic flow characteristics and driver behavior. So far there have been only a few studies that could give us some information about this kind of intersections and their specifics. Moreover, the current regulations do not provide procedures to determine their capacity. For the purpose to investigate and quantify the specifics of these intersections, some traffic flow characteristics and driver behaviour at unsignalized four-leg intersection with a bending priority road located in an urban neighbourhood in Žilina, Slovakia (see figure 1) were surveyed. The speed of major-stream vehicles was observed under free-flow conditions to receive...
maximum speed values. Driver behaviour (compliance with traffic rules, influences of potentially conflicting traffic streams on minor-stream drivers, and critical gaps) were observed during traffic peak hours by video processing. In the paper, the results are reported and analysed.

2. Priority ranks for traffic streams
A specific feature of intersections with a bending priority road is that both major and minor approaches are adjacent and not opposite each other. Such an asymmetric arrangement of major and minor streets causes traffic rules to combine giving way and priority-to-the-right, leading to different priority ranks for traffic streams compared to the conventional straight priority road (see figure 1). This causes the major streets entering the intersection not to have the same priority level themselves, but rather the right-hand major approach has priority over the left-hand major approach. The same is true for the minor approaches. Moreover, bending priority road at unsignalized intersection results to the different priority ranks of the same traffic movements. For example, there is the major-street through movement of Rank 1 (traffic stream B5) and Rank 2 (traffic stream A2), and the minor-street through movement of Rank 3 (traffic stream D11) and Rank 4 (traffic stream C8).

3. Survey results
3.1. Vehicle speeds at a bending priority road
When the priority road at an intersection is curved, vehicles have to move within a relatively small radius. As a result, their speed is slower than they would have travelled if the priority road ran straight through the intersection. Often the vehicles never reach the city speed limit of 50 kilometres per hour (km/h).

At the surveyed intersection where the radius of the major street is only 25 meters, vehicle speeds were measured under free flow conditions using a Bushnell Velocity speed gun. Measured values are shown in figure 2. The average speed in the inner lane (A to B on the right-hand diagram in figure 1) and the outer lane (B to A) were 28.6 and 32.7 km/h, respectively, with the mean almost 40% slower than the posted 50 km/h speed limit.

![Figure 1. The investigated four-leg intersection with a bending priority road in Zilina and the traffic stream priority hierarchy](image-url)
3.2. Violations of traffic rules

The specific nature of intersections where the priority road is bending make drivers prone to violate traffic rules. Along the priority road, some of them fail to signal a turn with their directional lights or signal too late, with an adverse impact on traffic safety and the magnitude of potentially conflicting streams affecting the minor stream vehicles.

Signalling turns from the major approaches A and B at the investigated intersection were monitored and the results are shown in figure 3. Almost all drivers signalled a left turn from the major street (about 95% to 99%), mainly from the major approach A, which is movement of Rank 2. However, less drivers signalled a right turn, with about 16% to 25% failing to use the right-turn indicator, mainly from the major approach A in the direction of the priority road.

At intersections with a bending priority road, some drivers deliberate violate priority rules for giving way to higher priority conflicting vehicles thanks to specific situations that do not occur at conventional intersections with a straight priority road. It can be seen in the example in figure 4, where a vehicle on the minor street (from C8) crosses the intersection at the same time as a non-conflicting higher priority vehicle (from A2 or A3) while another conflicting higher priority vehicle (from D11) is waiting to enter the intersection. Slovakian traffic laws require a driver on the minor street to give way to all conflicting higher priority vehicles, so the vehicle entering at D11 should first cross the intersection before the vehicle entering at C8. Table 1 shows the situations that can occur at four-leg intersections.
Figure 4. Example of specific situation opportunity of drivers from minor stream C8 to violate the priority rule

Table 1. Conditions in specific situations for minor traffic streams to violate the priority rules

| Minor stream | Higher priority conflicting stream | Non-conflicting higher priority stream |
|--------------|-----------------------------------|---------------------------------------|
| C9           | A1                                | B4                                    |
| C8           | D11                               | A2, A3                                |
| C8           | D10                               | A2                                    |
| C7           | D10, D11                          | A1                                    |
| C7 or D11    | A2                                | B6                                    |
| D11          | A1, A2                            | B5                                    |
| D10          | A1, A2                            | B4                                    |

Failures to give way were monitored at the least priority minor approach C at the surveyed intersection during peak hours and when there were long delays. Minor-stream vehicles crossing the intersection were recorded as well as any opportunity for drivers to violate traffic rules for giving way. For every specific situation listed in the table 1, a minor-street driver was monitored whenever he or she crossed the intersection whether or not priority rules were violated. The results from the traffic survey are shown in figure 5.

About 19% of specific situations for opportunity of drivers to violate the priority rules from all entering minor-street vehicles from C were recorded. Drivers from the lowest-priority traffic streams, such as turning left from C (C7) and crossing straight from C (C8), most often took the opportunity to cross the intersection even though they were violating priority rules (about 85% to 95% from the specific situations). About 60% of drivers turning right violated priority rules in these situations. About 16% of the total number of vehicles entering the intersection from the least priority minor approach C violated priority rules.

3.3. Conflicting and potentially conflicting traffic streams

Minor stream vehicles have to give way to higher priority conflicting vehicles before they enter the intersection. In figure 6, all conflicting traffic streams for all minor streams are highlighted in red on the matrix (e.g., the minor stream D10 has A1, A2, B5, B6 conflicting major streams). Besides these conflicting streams, some of the non-conflicting higher priority streams (potentially conflicting streams) sharing a lane with conflicting streams can affect minor-stream drivers when they enter the intersection. This is mainly related to some higher priority drivers who do not signal the change of direction or do it very late. Even when they signal the change of direction, minor-street drivers may hesitate and wait until there are also other indications that the conflicting higher priority vehicle is indeed turning.
Figure 5. Violation of priority rules

As a result of much more complicated situation to cross the intersection where the priority road is bending due to more complicated traffic rules and also non-signalling turns from major streets, there are two times more potentially conflicting traffic streams compared to a conventional four-leg intersection [6]. These are highlighted in blue on the matrix in figure 6, which also presents an example of conflicting and potentially conflicting streams for the minor traffic stream D10. The situations present how non-conflicting higher priority streams (A3 or B4) sharing a traffic lane with conflicting streams (A1, A2 or B5, B6) could affect drivers from the minor stream (conflicting streams are illustrated with red arrows and potentially conflicting streams with blue arrows).

| Minor stream | Conflicting and potentially conflicting traffic stream |
|--------------|-------------------------------------------------------|
|              | TS rank | I rank | II rank | III rank |
|              | TS      | A3 | B4 | B5 | B6 | A1 | A2 | D12 | D10 | D11 |
| II.          | A1      | 100% | 100% | 39% |
|              | A2      | 100% | 100% | 100% |
|              | D12     | 100% | 43% | 50% |
| III.         | C9      | 0%  | 32% | 100% | 42% | 100% | 19% |
|              | D10     | 43% | 33% | 100% | 100% | 100% | 100% |
|              | D11     | 100% | 100% | 52% | 63% | 100% | 100% |
| IV.          | C7      | 100% | 100% | 43% | 45% | 100% | 27% | 100% | 100% | 100% |
|              | C8      | 0%  | 100% | 100% | 16% | 100% | 33% | 100% | 100% | 100% |

Figure 6. Conflicting and potentially conflicting streams at the intersection with bending priority road (left) and an example for traffic stream D10 (right)
To see how large the impact of potentially conflicting streams is, the intersection was surveyed over several days. All possible situations involving potentially conflicting stream influences were monitored. The impacts of these streams were evaluated separately out of the total number of situations for each minor stream, presenting the percentage of situations where potentially conflicting vehicles affected minor-stream vehicles. The matrix in figure 6 shows the results of the survey. The impact of conflicting streams is taken into full consideration.

Most of the predicted potentially conflicting streams were confirmed, with the survey indicating only A3 having no impact on minor streams C8 and C9. The effect of the other potentially conflicting streams ranges between 20% and 60%. Stream B6 (turning right from the major street) had the most impact on minor stream D11 (opposite of traffic flowing from the minor street). Stream B6 had the least impact on minor stream C8, and stream A2 on minor stream C9 at less than 20%.

The effect of potentially conflicting streams is important to know for determination of a priority stream volume which consists of all conflicting traffic streams and also potentially conflicting streams sharing a lane with conflicting streams. The value of priority stream volume then affects a potential capacity of the minor traffic stream that can be calculated according to HBS by following equation:

\[
G = \frac{3600}{t_f} \times e^{-\frac{aq}{3600}(t_c - \frac{t_f}{2})}
\]

\(G\) - potential capacity of the minor stream [pcu/h],
\(t_c\) - critical gap [s],
\(t_f\) - follow-up headway [s],
\(q_p\) - volume of the priority stream for minor stream [veh/h].

With higher volume of potentially conflicting streams, a value of priority stream volume increase, which causes potential capacity reduction of minor streams. For some minor streams at the investigated intersection (C9, D10, D11, D12), reduction of the potential capacity was about 20-35% due to the potentially conflicting streams included in the priority stream volume calculation [6].

3.4. Critical gaps determination

The critical gap can be defined as the minimum time interval between major-stream vehicles that is necessary for one minor-stream vehicle to make a maneuver. Critical gap value reflects the driver gap-acceptance behaviour and this stochastically distributed value cannot be measured directly on the field. Only rejected gaps and accepted gap of each minor stream vehicle can be measured at the intersection. Consequently, several methods for critical gap estimation are presented in literature [1, 2, 3, 9]. In this paper, critical gap times have been estimated from the field data at investigated intersection for three through traffic streams A2, D11 and C8 (ranked 2, 3 and 4), by the most reliable Troutbeck’s MLM method.

The model of Troutbeck (1992) for estimating critical gaps is based on the Maximum Likelihood Method (MLM) assuming the log-normal distribution of accepted gaps (\(a_i\)) and corresponding the maximum rejected gaps (\(r_i\)) for each minor street vehicle. The likelihood function is defined as the probability that the critical gap distribution lies between the observed distribution of the maximum rejected gaps and the accepted gaps [8]:

\[
L = \prod_{i=1}^{n} [F(a_i) - F(r_i)]
\]

\(L\) - maximum likelihood function,
\(a_i\) - the logarithm of the accepted gap of vehicle i,
\(r_i\) - the logarithm of the maximum rejected gap of vehicle i,
\(F(a_i), F(r_i)\) - cumulative distribution functions for the normal distribution.
The logarithm of function (2) is as follows:

\[ L = \sum_{i=1}^{n} \ln[F(a_i) - F(r_i)] \]  

(3)

The parameters of the critical gap distribution function, the mean \( \mu \) and variance \( \sigma^2 \), are obtained by maximizing this likelihood function, by solutions when the partial derivative of equation (3) is equal to zero. They can be simplified as follows:

\[
\begin{align*}
- \sum_{i=1}^{n} \frac{f(a_i) - f(r_i)}{F(a_i) - F(r_i)} &= 0 \\
- \frac{1}{2\sigma^2} \sum_{i=1}^{n} \frac{(a_i - \mu)(a_i - \mu) - (r_i - \mu)(r_i - \mu)}{F(a_i) - F(r_i)} &= 0
\end{align*}
\]  

(4)

\( f(a_i), f(r_i) \) - probability density functions for the normal distribution with parameters \( \mu \) and \( \sigma^2 \).

According to Troutbeck’s method the probability density functions \( f(a_i) \) and \( f(r_i) \), distribution functions \( F(a_i) \) and \( F(r_i) \) were calculated for each logarithm of accepted gap \( a_i \) and maximum rejected gap \( r_i \). The likelihood parameters: the mean \( \mu \) and variance \( \sigma^2 \), were obtained by iteration process programmed in MS Excel. Finally, the values of mean of the critical gap \( t_c \) and variance \( s^2 \) were calculated according to equations [8]:

\[ t_c = e^{\mu+0.5\sigma^2} \]  

(5)

\[ s^2 = t_c^2 \cdot (e^{\sigma^2} - 1) \]  

(6)

As an example, distribution functions of the maximum rejected gaps \( F_r(t) \), accepted gaps \( F_a(t) \) and the estimated critical gaps by Troutbeck’s MLM \( F_{tc}(t) \) for the traffic stream D11 are shown in figure 7 (left). The plot of the normal probability density function for this traffic stream is also shown in figure 7 (right).

Figure. 7. Example of critical gap estimation according to Troutbeck’s MLM for traffic stream D11.

For three through traffic streams A2, D11 and C8 (ranked 2, 3 and 4), figure 8 compares the critical gap values estimated by the MLM method with the Slovak regulations TP 102 values valid for conventional rural unsignalized intersections [7].
The critical gap value for each individual traffic stream rises with higher priority rank. The value of critical gap for traffic stream A2 (major-street through movement of Rank 2) is the smallest (5.5 seconds). It is about 1.5-2.0 seconds less than the values of traffic streams D11 and C8 (minor-street through movements of Rank 3 and 4). This is due to stream A2 being the major traffic stream with higher priority and an easier traffic situation for manoeuvring. In addition, this traffic stream has no more potentially conflicting streams that would affect it (see figure 6), so this value corresponds to the critical gap value listed in Slovakian regulations TP 102 for similar movement and priority rank [7]. However, the situation is different for traffic streams D11 and C8, which are minor traffic streams with lower priority. The values of critical gap for these traffic streams are 7.05 seconds and 7.44 seconds, respectively and they differ more significantly from the TP 102 values for the corresponding priority rank. The reason could be the more complicated traffic situation and the higher number of potentially conflicting streams at the intersection with bending priority road [4].

4. Conclusion
A specific feature of intersections with a bending priority road is that both major and minor approaches are adjacent and not opposite each other. Such an asymmetric arrangement of major and minor streets causes traffic rules to combine giving way and priority-to-the-right, leading to different priority ranks for traffic streams and other specifics compared to conventional intersections with straight priority road. To investigate and quantify these specifics, an unsignalized four-leg intersection with a bending priority road in an urban area of Zilina, Slovakia, was chosen and traffic there was surveyed.

The results show vehicles moving along the bending priority road about 40% slower than the city speed limit of 50 kilometres per hour. About 16% to 25% of drivers turning right from the major streets did not signal the change of direction or signal too late, mainly in the direction of the priority road.

At intersections with a bending priority road, there are specific opportunities for drivers to violate the priority rules that do not occur at conventional intersections with a straight priority road (minor-street vehicle crosses the intersection at the same time as a non-conflicting higher priority vehicle while another conflicting higher priority vehicle is waiting to enter the intersection). About 16% of the total number of vehicles entering the intersection from the least priority minor approach during peak hours and long delays took the opportunity to cross the intersection even though they were violating priority rules.

There are two times more potentially conflicting traffic streams compared to an intersection with a straight priority road and the effect of these potentially conflicting streams to the minor-stream drivers has ranged between 20% and 60%.
The paper demonstrates that the critical gap values for the same movements more significant differ according to major/minor street and rank of priority. Values of critical gaps for straight traffic streams of third and fourth priority rank were determined to be about four-tenths to nine-tenths of a second higher in comparison with values listed in Slovakian regulations TP 102 for conventional rural unsignalized intersections.

Values of the critical gaps estimated for each minor traffic stream only from rejected and accepted gaps in conflicting higher priority traffic streams could be affected by the potentially conflicting streams. If the potentially conflicting stream influence is involved in the calculation of the priority stream volume, it should be eliminated in the critical gap values; because both of them are inputs for calculation of a minor stream potential capacity. This gives a space for another research focused on the specifics of unsignalized intersections with bending priority roads.

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