Life-saving effects of road markings on bends

Der Beitrag von Bodenmarkierungen in Kurven zur Unfallreduktion

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1 Abstract

In 2017, new road markings were added to eight popular motorbike routes in Austria, predominantly on blind left-hand bends and in the form of bars or ellipses. This measure was successful in encouraging motorcyclists to avoid driving over the road markings. The riders' trajectories significantly changed towards a safer lateral position in the outside part of their lane.

Based on this experience, several bends on typical motorbike routes in Luxembourg were equipped with bar markings, based on a similar concept. Before-and-after-observations showed that road markings vary in effects, e.g., are not as effective on bends with good forward visibility. Besides these effects, this paper and presentation will highlight the opinion-forming process and resistance which had to be overcome as well as the process of design and practical implementation.

Meanwhile, researchers revisited the eight bends (= routes) in Austria. Long-term effects were investigated. It appeared the elliptic markings were even more effective than shortly after implementation. Bar markings improved rider behaviour to an even greater extent and fully caught up with elliptic markings. Moreover, the accident analysis found considerably fewer crashes in the after-period.

During the summer of 2019, 19 bends were equipped with road markings as one of the activities of a motorbike safety program of the Tyrolean regional government with immediate impact as the main goal. On average, there were 13 injuries and 0.6 deaths annually during a seven-year (before) period on these bends. In the 2.5-year after-period, 4 injuries were registered. After accounting for the massive impact of the Covid 19 pandemic on exposure (approx. 10% less commuter traffic, 40% less leisure riding), an 80% decrease in injuries was observed, and there were no more fatalities on the bends with road markings.

2 Kurzfassung

Auf acht beliebten österreichischen Motorradstrecken wurden 2017 in überwiegend unübersichtlichen Linkskurven neuartige Bodenmarkierungen in Form von Ellipsen bzw. Balken entlang der Mittellinie aufgebracht. Diese Bodenmarkierungen stellen eine Hilfe für Motorradfahrer dar, um die Kurve sicher zu durchfahren. Dabei wurde erfolgreich ausgenutzt, dass Motorradfahrer das Überfahren von Bodenmarkierungen meiden. Es wurden kurzfristig signifikante Veränderungen der Fahrlinien von Motorradfahrenden erreicht.

Darauf aufbauend wurden in Luxemburg mehrere typische Motorradstrecken auf Basis eines ähnlichen Konzepts mit Bodenmarkierungen (nur Balkenmarkierung) versehen. Auch hier wurden vor und nach der Aufbringung der Markierungen die Fahrlinien beobachtet. Es zeigte sich, dass die Markierungen nicht in allen Kurven gleich erfolgreich angewendet werden können, beispielsweise sind die Effekte in übersichtlichen Kurven auch vorhanden, jedoch geringer. Neben den Bodenmarkierungen selbst geht dieses Papier auch auf den Meinungsbildungsprozess ein, beleuchtet die Ressentiments, die zu überwinden waren, und stellt die Erfahrungen mit der praktischen Umsetzung und Gestaltung dar.

Währenddessen wurden in Österreich drei Jahre nach der Installation die acht Kurven (= Strecken?) erneut besucht und die längerfristigen Effekte erhoben. Dabei zeigte sich, dass Ellipsenmarkierungen noch besser wirkten als 3 Jahre zu vor; vor allem aber die zunächst weniger wirksamen Balkenmarkierungen in der Wirkung vollends zu den Ellipsen aufschließen konnten. Ferner zeigte eine Unfallanalyse deutlich geringere Unfallzahlen nach der Herstellung der Bodenmarkierungen im Vergleich zum Zeitraum davor.

Im Sommer 2019 wurden in im Zuge eines Motorradsicherheitspakets der Tiroler Landesregierung mit dem eine unmittelbare Reduktion des Unfallgeschehens angepeilt war, 19 Kurven mit Bodenmarkierungen in Ellipsen- oder Balkenform beklebt. In diesen Kurven waren im Beobachtungszeitraum 2012 bis 2018 in Summe durchschnittlich 13 Verletzte und 0,6 getötete Motorradbenutzer pro Jahr registriert worden. Diese Tiroler Motorradsicherheits-Initiative wurde 2022 wiederholt. Dabei wurde festgestellt, dass – auch wenn man den massiven Einfluss der Covid19-Pandemie berücksichtigt (etwa 10% weniger Zweckverkehr, 40 % weniger Freizeitverkehr mit Motorrädern) – die Zahl der verletzten Motorradfahrenden in den betrachteten Kurven um 80% zurückging, getötete gab es in den Kurven mit Bodenmarkierungen gar keine mehr.

3 Introduction

The two most common types of accidents in motorbike accidents are "falling off the vehicle" and "leaving the road to the right in a left-hand bend". It has been shown that cornering is often the starting point for such accidents. In studies (Winkelbauer, Bagar, 2013), 5 out of 6 motorcyclists drove so far to the left that they would have had to correct their trajectory in case of oncoming traffic. In most cases, motorcyclists manage to avoid oncoming traffic, but the second necessary correction of the trajectory fails due to "lean angle anxiety" (see below).

The use of road markings to influence the line choice of motorcyclists in bends was already reported here in 2018 (Winkelbauer, Bagar, Höher, Wollendorfer, 2014). At that time, there were empirical values from initial tests on a combination of bends on the Carinthian side of the South Styrian border road ("Soboth"). There, road markings in a W-shape were stuck on the outside of a guideline in order to visually widen the central separation of opposing traffic. Such markings, according to recognised expert opinion, have less of an effect on motorcyclists through their visual impression, but rather through the very widespread stereotype among motorcyclists that road markings are slippery and that one must keep away from them, especially when driving at an angle. This is also taught in driving schools and cannot be got rid of despite the very sound regulations on the skid resistance of road markings. Currently, the skid resistance of road markings must not differ significantly from the skid resistance of the surrounding road. However, when newer road markings are worn out, much older markings may very well come to the surface that do not comply with these regulations.

The markings along the Soboth proved to be effective. After the application, motorbike accidents were reduced to zero in this area, but when the markings faded after about three years, accidents began to re-occur. Only later were more detailed scientific investigations carried out. The first step was an observation of the trajectories of motorcyclists, which was carried out by the KFV on behalf of the Carinthian provincial government (Winkelbauer, Schneider, Strnad, Braun, Schmied, 2017). The subject of this study was only two bends. The effectiveness of different forms of marking was examined. The reason for this was that the W-shaped markings had occasionally been interpreted by motorists as a no-go area. Although this had not caused any accidents, it was reason enough to look for better solutions. The aforementioned study showed that elliptical markings were the best solution. These are not confused with other markings and have no other legal significance. If they are stuck on at an angle of about 45 degrees to the direction of travel, they give the impression of a "deflector".

Subsequently, several studies were carried out to investigate the effectiveness of road markings in influencing road positioning and the effects on the occurrence of accidents at various locations. The results are presented in this paper.

3.1. Motorbike Accidents

In the last 20 years, one cannot speak of a steady "trend" in accident occurrence involving motorbikes. Due to the Corona pandemic, the years 2020 and 2021 are completely out of line. Motorcyclists were urged not to put themselves in danger unnecessarily and to refrain from unnecessary journeys because hospital capacities were needed for Corona patients. Cycling experienced a boom that was most likely not triggered exclusively by the pandemic. Single-track motor vehicles were also partial substitutes for people who wanted to avoid public transport. These circumstances interfere with an evaluation based on a time-series analysis.

The constant boom (in motorcycle numbers) must be considered in the development of accidents involving motorbikes. Since 2000, the number of motorbikes in Austria has increased by 20,000 to 25,000 units per year; in the two Corona years, new registrations of 40,000 to 50,000 units per year were in the range of the previous years. The fact that this enormous growth of about 5% per year did not lead for quite some time to an equally large increase in the number of accidents was probably mainly due to the generally improving safety levels in Austria and to technical improvements to vehicles. However, 2012 saw a turnaround; both killed and injured motorcyclists have slowly but steadily increased since then, until the pandemic caused the numbers to plummet. This drop is almost certainly due to a decrease in exposure - i.e., mileage. No studies are known on the question of whether this decline is a consequence of the previously mentioned appeals to refrain from non-essential driving or the result of home office and short-time work.

Generally speaking, it can be said that motorbike accidents are the sum of two completely different worlds. Most recently, in 2012 (Winkelbauer & Schwaighofer, 2012) it was found that about three quarters of Austrian motorcyclists are predominantly recreational riders. They go for a ride on their motorbike after work or at the weekend to relax, or they go on holiday by motorbike. About a quarter of motorcyclists are mobility-oriented. They mainly ride in urban environments, take advantage of the free parking for motorised two-wheelers, also hardly have to look for parking space and save time in traffic jams. They often ride scooters, wear little protective clothing and tend to have fewer serious accidents. Intersection accidents and rear-end collisions dominate among these "functional riders". Single-vehicle accidents dominate among recreational riders. Overtaking accidents are particularly severe because they often involve oncoming traffic and overtaking is done at a higher speed than other manoeuvres.

3.2. Cutting curves

The typical recreational rider is looking for winding roads. Often this is also related to scenic beauty, but the experience of riding dynamics, the challenge of a demanding route and the sense of achievement after a successful ride are the dominant motives for such motorcyclists. In this respect, cutting curves seems absurd. People look for curvy routes, often even accept a long journey, and then "bend the curves straight", as it were, by cutting them. No studies could be found on the actual reasons for this behaviour, but it seems reasonable to assume that the triangular relationship between curve radius, speed and lean angle is decisive: higher speed in a curve is made possible by a larger radius (i.e., curve cutting) or greater lean angle. Road safety training also revealed that the same motorcyclists who were first filmed with their heads well beyond the centre line were firmly convinced that they had stayed within their lane. This observation is the reason why video is used in such training courses. And experience shows that the course participants react very surprised when they see from the videos how far over the centre they were.

Motorcyclists often ride in groups. There are several reasons for increased risk in this context: the will to keep up with others in the group can lead to exceeding personal limits (Lang, Kühn, 2020). To compensate, curves are shortened. The fault lies not only with the affected riders themselves, but above all with the rider in front, who overtaxes members of the group. In more than half of the accidents occurring during group rides, members of one's own group are the 3rd party in the accident.

3.3. Lean angle anxiety

Cornering radius, driving speed and lean angle are mathematically related when cornering with single-track vehicles. There are limits to the lean angle, due to the grip of the tyres on the road surface, the ground clearance of the vehicle and the ability of the driver to adopt the lean angle required by the speed and radius.

The term Schräglagenangst (lean angle anxiety) was first recorded in the German-speaking world by the journalist Bernd Spiegel. In his book "Die obere Hälfte des Motorrads" / The upper half of the motorbike (Spiegel, 2015), he wrote about this phenomenon, which had hardly been addressed until then. He argued that motorcyclists who are not specifically trained have a natural lean limit of about 20 degrees, that this can be explained anthropologically and that it also occurs in the same way when running or riding. Meanwhile, it is known that motorcyclists consistently ride at higher lean angles (Winkelbauer, 2018). The German Federal Highway Research Institute has also had the phenomenon studied in detail with regard to the justification of the term "fear" (Scherer et al, 2021). The study showed that motorcyclists have an individual lean angle limit. This is slightly variable, depending on the context

and the prevailing conditions. It is not possible to exceed it. To put it simply: If a left turn at the chosen speed is not feasible, or if the planned line of travel is disturbed by oncoming traffic (as a result of a too narrow line of travel), this ends either in an uncontrolled braking manoeuvre and a crash, or in leaving the lane - still sitting on the motorbike.[1] However, the study also found that motorcyclists do not significantly undercut their lean limit. This means that their safety reserves are always low in all bends where the driving speed is selected on the basis of the bend radius and maximum lean angle. In the accident statistics, however, resulting accidents are not only found as "swerving to the right in a left-hand bend" (about 10% of all motorbike accidents), but also as "falling off the vehicle" because jerk-reaction braking leads to an immediate fall (about 12% of motorbike accidents). Only rarely do motorcyclists collide with oncoming traffic in left-hand bends (about 2%). Reaching the lean angle limit is such an intense experience and its effect so extreme that it can be described as a phobia or even "fear", in line with medical phenomena.

4 History and Research

The findings collected in the pilot study were positive enough to subject them to a detailed investigation (i.e., the first evaluation study). Their good results led to great interest in the professional world and to several further applications and investigations, which are presented chronologically below.

4.1. Pilot Study

The markings along the Soboth proved to be effective. After the application, motorbike accidents were reduced to zero in this area, but when the markings faded after about three years, accidents began to re-occur. More detailed scientific investigations were carried out only later. The first step was an observation of the trajecgories of motorcyclists, which the KFV carried out on behalf of the Carinthian provincial government. The subject of this study was only two bends. The effectiveness of different forms of marking was examined. The reason for this was that the W-shaped markings had occasionally been interpreted by motorists as a barrier. Although this had not caused any accidents, it was reason enough to look for better solutions. The aforementioned study showed that elliptical markings were the best solution. These are not to be confused with other markings and have no other legal significance. If they are stuck on at an angle of about 45 degrees to the direction of travel, they give the impression of a "deflector".

[1] For motorcyclists, there are - to put it bluntly - only two types of curves: either the speed determines the lean angle or the lean angle determines the speed. Motorcyclists negotiate narrower bends at a speed that suits their individual lean angle tolerance. For wider bends, the lean angle is determined by the driving speed, which is based on the speed limit or visibility, for example.

4.2. Rakitna, Slovenia

This is a very beautiful, winding excursion route about 30 km south of Ljubljana. On an approximately 10 km long section of road 643, dynamically oriented motorcyclists would measure their driving times and publish them on the Internet, and the number of accidents was correspondingly high. Here, the same W-shaped markings as on the Soboth were placed on numerous bends. According to the responsible official of the Slovenian administration, this led to a massive reduction in the number of accidents. The markings were massively opposed by the motorcyclists' associations, but the initially strong resistance gave way over time. Time trials continued on the route, but it was no longer the motorcyclist who ventured furthest into oncoming traffic who set the best times. The competition was shifted to the rider's own side of the road. This made the illegal races safer and was ultimately appreciated by the motorcyclists. There was no scientific study of the curve lines, the accidents or the opinions of the motorcyclists.

4.3. First evaluation study: rider positioning on nine bends

In order to create a sound data basis for the further application of road markings, nine bends were selected in 2016 for a thorough before-and-after study in cooperation with the provincial administrative authorities of Lower Austria, Burgenland and Carinthia (*Winkelbauer, Schneider, Strnad, Braun, Schmied, 2017*). A video camera was set up at the entrance to the bend, at the apex and at the exit from the bend and left in place for one day. This was usually sufficient to reach the target of 500 observed motorcyclists. After that, ground markings were glued on. As in almost all other applications, the extremely grippy Stamark 380 film from 3M was used for this. The after-observation followed in the same way. The videos were evaluated with the support of automatic image data recognition ("machine vision"). In addition to the elliptical markings already shown, a second design was investigated: as suggested by the Lower Austrian provincial government, bar-shaped markings were designed based on the concept of a "psychological brake". Here, 50cm wide markings are used on the right and left edges of the lane, leaving a progressively narrower lane as the bend is approached. As with the elliptical markings, the parts along the centre line are sized in order to cover the area of the lane that motorcyclists should not enter and in order to maintain sufficient distance from oncoming traffic. The markings on the outer edge of the bend serve to visually narrow the bend (Figure 1).

Figure 1: bar markings (Arlberg road)

Of the nine bends considered, one was not marked due to a blockage caused by a landslide. One bend at the Loiblpass was not included in the general evaluation due to the special circumstances (e.g., narrow bend radius, missing guiding line). On the remaining bends, there was for the most part a clear improvement in the trajectories of motorcyclists. Figure 2 clearly shows that fewer motorbikes rode in the danger zone with both elliptical and bar markings. This is labelled "inside" in the graph and includes all motorbike rides where the tyres were riding in the left third of their own lane or beyond the centre line. The middle and right thirds of the own lane were defined as the safe zone in this sense.

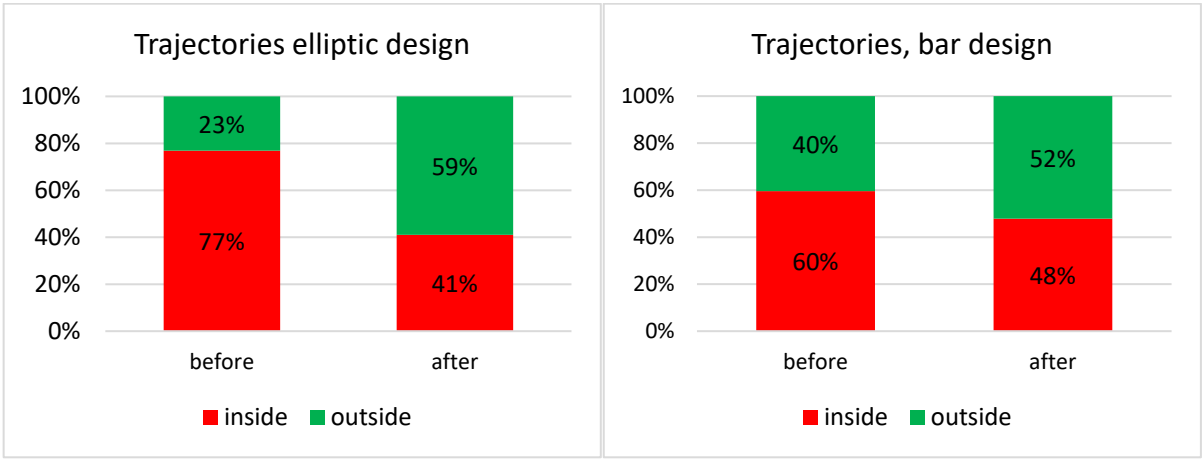

Figure 2: Riders' trajectories at the apex of the bend before and after applying the markings

In this study, the ellipses (see example in Figure 3) had a better effect than the bars. Measurements were also taken at the beginning and end of the bends; these showed desirable changes, although not as clearly.

In addition, surveys were carried out at restaurants frequented by motorcyclists in the vicinity of the marked bends. Understanding of and experience with the markings proved to be positive throughout. The majority of motorcyclists considered the measure sensible and necessary, understood the meaning and also believed that they had behaved correctly. The study created the basis for further applications of the markings.

Figure 3: Ellipse markings in the Namlos Valley

4.4. Großglockner

Due to the initial success of the measure, KFV was invited by Großglockner-Hochalpenstraßen-AG in 2017 to install elliptical road markings on six bends. Special attention was paid at the time to the stricter standard of care in the context of liability to which the Großglockner-Hochalpenstraßen-AG is subject as a toll operator. However, the markings proved to be legally unproblematic: elliptical and bar markings may be affixed as ground markings with a pure traffic guidance function within the meaning of § 55 para 1 StVO (i.e. the Austrian road code). According to § 98 (3) StVO, the road owner may install the markings without an official order because the markings do not express a traffic prohibition or order; however, the authorities may also prescribe their installation or removal.

A follow-up study was only conducted here on a small scale (Winkelbauer, Senitschnig, 2018). The most important finding was that motorcyclists riding on or to the left of the ellipses clearly and significantly more often corrected their line of travel due to oncoming traffic than those riding to the right of the markings. From the perspective of driving dynamics and the presumed causes of accidents, this is a significant and very positive finding.

4.5. Styria

In 2017, the Styrian authority also decided to implement safety measures on bends with above-average motorbike accidents by means of road markings. Fourteen bends were selected. The unusual thing about the Styrian solution was that it was planned on a computer (Figure 4). In contrast to all previous cases, where test rides were always carried out by experienced motorcyclists before the final marking, a fully dimensioned plan was drawn up on the computer based on an orthophoto and theoretical knowledge of correct trajectory selection, which was then implemented by a marking company. Subsequent driving tests showed that this approach also leads to a very satisfactory result. However, this measure was not evaluated.

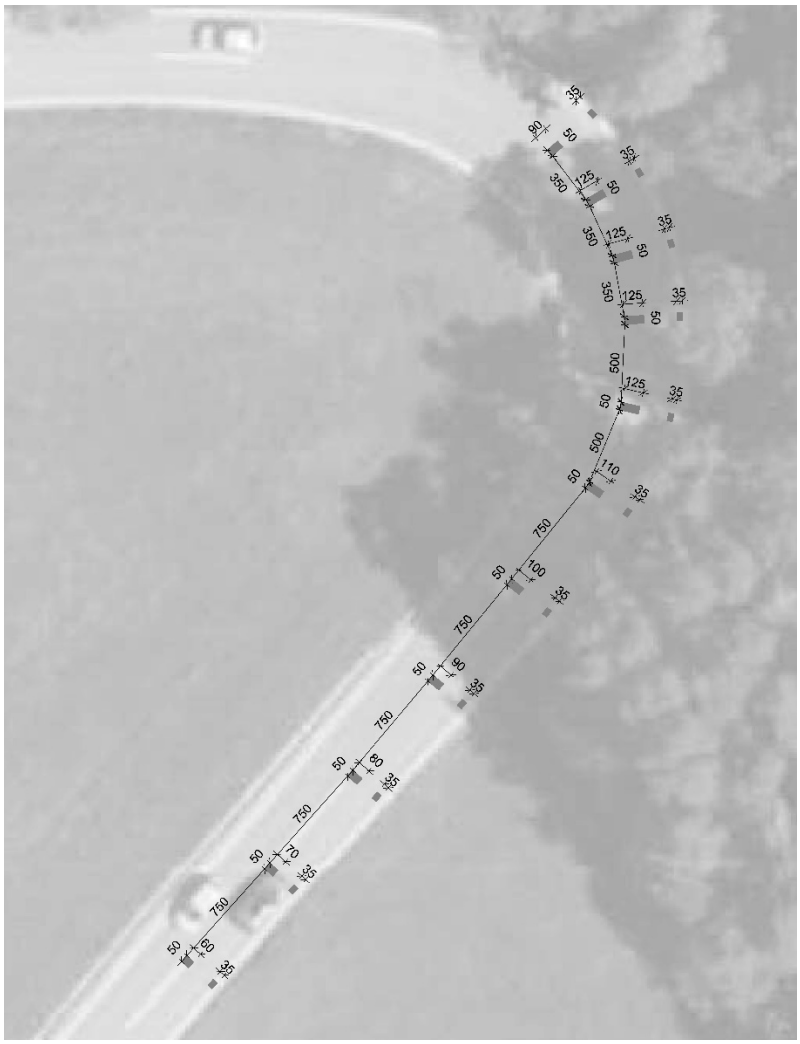

Figure 4: Computer aided design of road markings in bar shape

4.6. Tyrol, 2019

Traffic accidents in Tyrol are characterised by an above-average proportion of motorbike accidents, and these by a high proportion of foreign motorcyclists. The authorities of the province therefore decided to take a new approach. Funded by the Tyrolean Road Safety Fund, a project was launched with the aim of implementing safety measures to take effect in the same year. As a basis, motorbike accidents throughout Tyrol were investigated. Without regard to the usual definitions of accident blackspots, a work programme for about 60 accident-prone bends was determined on the basis of official accident statistics, but also with the help of the experience and expertise of the local road maintenance and police departments. In July and August 2019, the bends were mostly visited together with road maintenance officers and road markings were immediately installed on a total of 19 bends, mostly on typical motorbike routes. In some cases, other measures were carried out immediately or agreed for early completion, for example the installation of additional guide angles or the erection of danger signs. At

the end of the year, an informal evaluation of the experience was carried out; the road maintenance managers only gave positive or neutral feedback.

4.7. Tulbingerkogel

The roads around the Tulbingerkogel via the "Dopplerhütte", Königstetten, Katzelsdorf, Passauerhof, Buchenhof and Hainbuch are a typical motorbike route of the Viennese motorbike scene. Motorcyclists do their rounds there, often a dozen a day, partly in one direction and partly in the other, and sometimes they are timing themselves. The residents suffer from the noise, especially at weekends, and the accident figures are correspondingly high. In addition to the bends with above-average accidents, bends with bar markings were also marked here, where the fire brigade or road marshals often retrieve motorbikes from the forest. In order to test a possible influence on noise pollution, bends were also marked that are cut particularly often for the purpose of accelerating on the following straight, and in which a great deal of noise is caused by the acceleration.

Immediately after marking, the effect was noticeable - although not scientifically studied in detail. According to the municipal officials, the motorcyclists came in smaller numbers, did not stay as long, drove more slowly at the crucial points, the complaints from the population were not forthcoming and the fire brigade did not have to pull any more motorbikes out of the forest. No traffic accidents with personal injury were reported after the marking.

The measure cost the municipality of Katzelsdorf about 3,000 euros and, according to their feedback, was "worth every cent". It remains to be seen whether the effect is sustainable. It is difficult to ascertain whether or to what extent this measure leads to a local shift in motorbike journeys.

4.8. Second study: Lasting effects, accident occurrence

One of the crucial questions in road safety measures is almost always whether they have a lasting effect or are merely a flash in the pan. In order to observe changes in accident occurrence, one needs - as macabre as this sounds - enough accidents and thus enough time. As soon as the complete accident data from the three years after the installation of road markings was available as part of the first large study, a further evaluation was therefore carried out. Of the eight bends marked in 2016, Weissenseestraße was closed for renovation in 2020, but the remaining seven bends were visited again, the condition of the markings was checked, video observations were made, and the accident occurrence was analysed.

The surprising result (Figure 5) was that the bar markers had caught up with the ellipses and both interventions can now be considered equally effective. Even more surprising was that the ellipses also increased in effectiveness compared to 2016. Most of the improvements are statistically significant, so

the effectiveness can be considered proven. However, there was also a significant deterioration on one bend on the Lorettoer Straße (L213 in Burgenland). It is suspected that the installation of edge lines, which had taken place in the meantime, does not match the trajectory provided by the bars. It is also a fact that the L213, like the Tulbingerkogel, is driven by the same "loop drivers" over and over again. Since the choice of trajectory in 2020 was similar to that before the intervention in 2016, it can be assumed that the drivers who know the area are no longer bothered by the markings.

The observed decrease in the number of accidents was particularly pleasing. In the observed bends, the number of accidents with personal injury decreased from 16 to 7. This change is considerable, but in absolute terms too small to be significant.

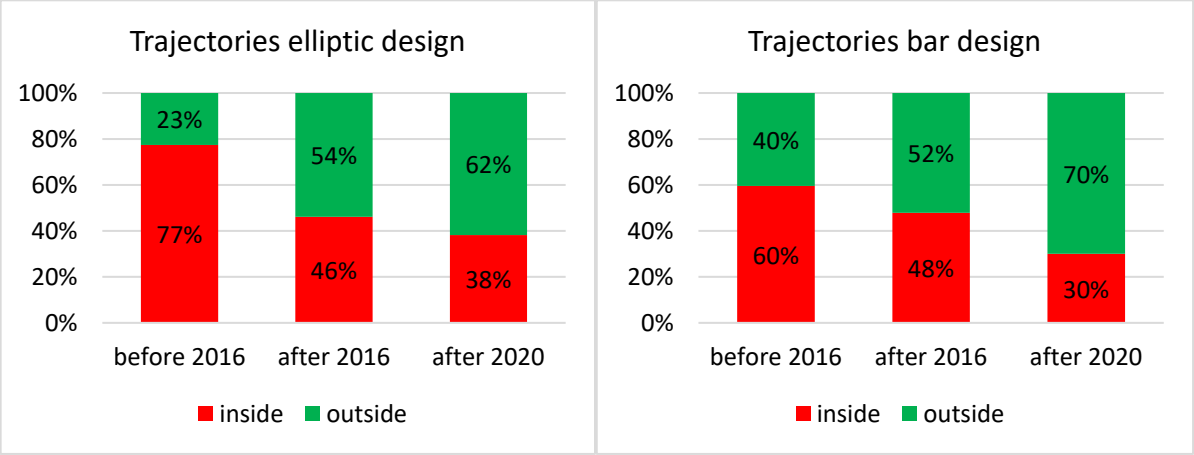

Figure 5: Riders' trajectories at the apex before, after and four years after intervention

4.9. Motorbike accident blackspots: Update Tyrol 2022

In 2021, the Tyrolean provincial government granted funding for a renewed inspection of the roads with regard to accident blackspots. Again, it was planned to immediately install road markings at suitable accident sites. In the course of this process, a follow-up investigation of the accident events of the previous years was also carried out. In the period from 2012 to 2018, an average of 6.3 lightly injured, 6.4 seriously injured and 0.57 fatally injured motorcyclists were registered annually at the 19 bends that were later provided with road markings. In the 2.5 years following the installation of the markings, a total of 2 slightly and 2 seriously injured motorcyclists were recorded. Due to the Covid19 pandemic, the number of riders passing relevant counting points (i.e., those on typical motorbike excursion routes) decreased by about 40%. This means that there was a net 80% reduction in accidents on the bends after the introduction of the road markings. However, due to the extremely small number of accidents after the intervention, it would be premature to speak of a "decrease".

5 Application in Luxembourg

5.1. Initial situation

In 2018, a road safety inspection of the national road N25 between Wiltz and Kautenbach in the north-west of the country revealed an atypical accident cluster based on the 2013-2017 accident data. This did not match the traffic pattern or the accidents on other roads in Luxembourg. Traffic was not distributed over the usual five weekdays and was not lower at weekends, but rather increased at weekends. Most of the recorded accidents happened at the weekend (Figure 6) and this in the best weather and often involving motorcyclists (Figure 7). Luxembourg is a popular destination for motorcyclists and has been struggling for years with a not inconsiderable number of fatal motorbike accidents. It soon became clear that the N25 was such a motorbike route in the north of the country. Besides commuters and local traffic, it attracts many motorbike tourists, especially at weekends and during holidays. The winding back roads in the rural idyll of the Ardennes are the big attraction for motorcycle-loving tourists.

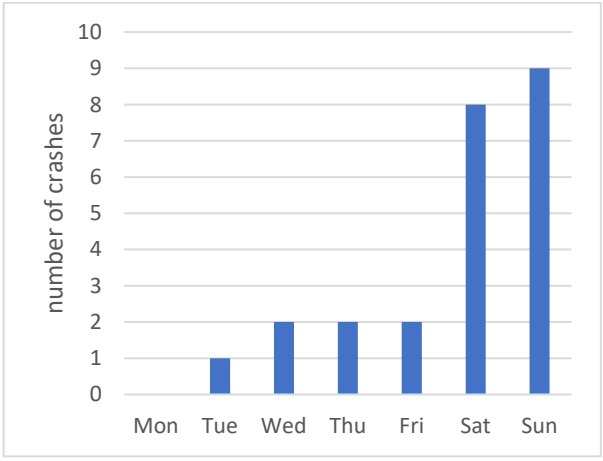

Figure 6: Motorbike Crashes by day of the week, N25 from Wiltz to Kautenbach, Luxembourg

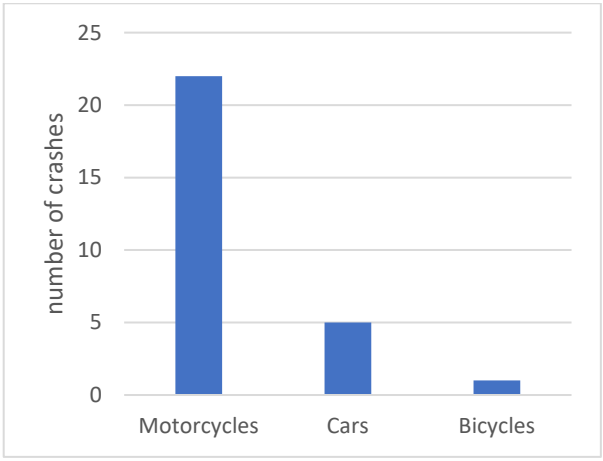

Figure 7: Crashes by mode, N25 from Wiltz to Kautenbach, Luxembourg

The problem to be solved on many of these routes are the ends of bends that cannot be seen, or sequences of bends that cannot be seen. Incorrect entry into the bend requires a correction of the trajectory, i.e., either cutting the curve into oncoming traffic or opening the steering angle and leaving the road at the exit of the bend. However, this ground marking should be understood intuitively and, if possible, have no impact on other road users.

Based on this problem, the Luxembourg National Road Administration looked for solutions abroad and found what they were looking for in Austria. The Austrian Road Safety Board (KFV) had already tested various solutions with road markings (circles, ellipses, ovals, bars, etc.) for safe cornering within the framework of its studies. After an exchange with the KFV, it was decided to launch a pilot project and the question then arose as to how this could be implemented in Luxembourg in the short term and in accordance with Luxembourg law.

Here are a few insights from the discovery phase and then also from the subsequent analysis:

What provisions were there in the road traffic regulations?

Geometric shapes for markings are not specified in the Luxembourg Road Traffic Regulations. However, white lines are described and for transversal bars it is not specified how they are to be arranged (except as a stop line). Nevertheless, within the framework of the *Permission de voirie* i.e., "road construction permit", there are lateral bars within the framework of town entrances. These are familiar to Luxembourgish motorists. Although round shapes have achieved the best results in Austria, they are not provided for by law and it was not possible to obtain any in the short time available (March to June 2018).

How can these lateral bars be applied?

In Austria, geometric plans were made of how the markings should be applied. We also followed this approach. However, it turned out to be more effective to select the bends in advance on the site plans and to indicate the crossbars provisionally on site with adhesive strips and to have them driven on by experienced motorcyclists, in our case by instructors from the Luxembourg police motorcycle squad (Figure 8).

Figure 8: Test ride by a police rider

How should the quality of the bar marking be?

The quality (skid resistance) of the marking must in any case be better (higher) than that of the road surface. This was and still is the case and is checked annually. Our advantage was that we could rely on our own marking team, which then quite quickly got the hang of it and could proceed identically on the further routes. A 2-component cold plastic coating was used.

What should the bend characteristics be like?

The markings work best on bends where the end or the further course of the road is not visible at the beginning. This means that it is not obvious to the driver beyond the apex what the further course of the road is. If this is not the case, the curve is cut more often because there is a visible trajectory. Then there must also be a dashed centre line, with a spacing of 3 / 3 / 3 [m] and, of course, there should be guidelines at the edges of the carriageway to define the carriageway neatly.

What did the before and after analyses show?

On several stretches it was also possible to carry out before-and-after analyses by video recording at selected bends in order to check the driving behaviour of both motorcyclists and other road users. Therefore, the road was divided into 3 different zones (Figure 9) and different time periods were checked at the weekends.

Figure 9: Areas for assessing the trajectory

5.2. Results

Before situation

The analysis of the data obtained in the first step regarding driving behaviour yielded the following results:

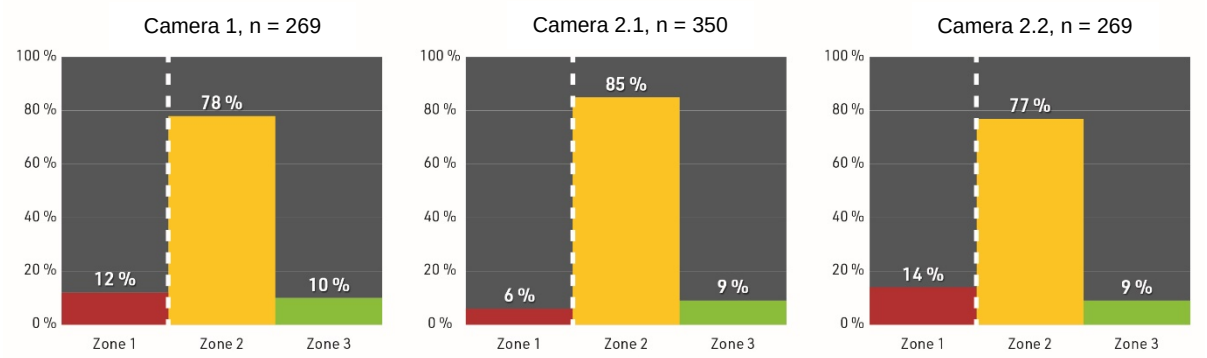

Figure 10 Trajectories of riders before the intervention

From the diagrams of the first weekend without safety markings, it emerged (Figure 10) that between 9% and 10% of the motorcyclists choose a safe curve line on the respective bends and drive through the bend "in the green zone", so to speak. In contrast, 77% to 85% of the motorcyclists drive in the orange zone and between 6% and 14% in the red zone and even to the point where their behaviour constitutes a high accident risk.

After situation

After the application of the lane markings, the driving behaviour was again analysed by video recordings on the same three bends. The analysis was carried out on three different weekends - the following weekend, two weeks later (Figure 11, Figure 12), two months later, and always on weekends during the peak motorbike season - in order to draw conclusions about a possible long-term effect. Between 120 and 350 motorcyclists were recorded on each weekend. The evaluation of the data obtained showed that driving behaviour had improved for the better (Figure 13).

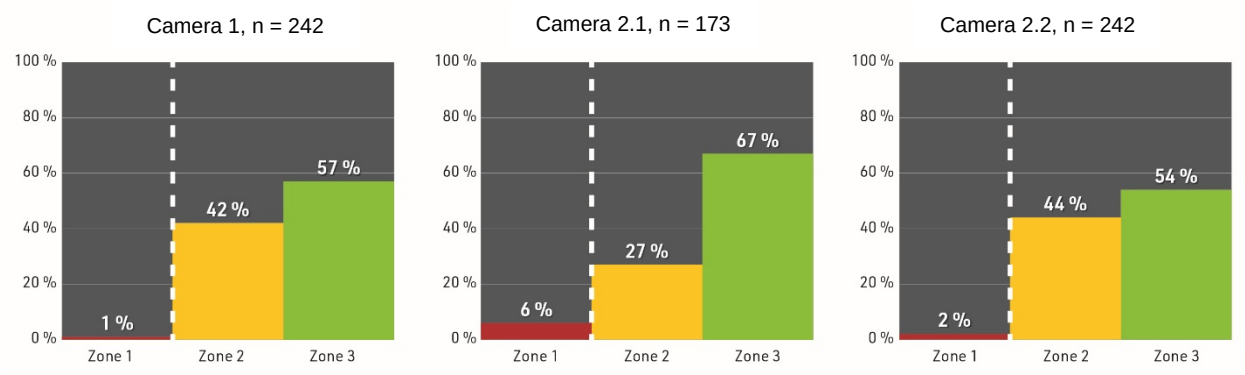

Figure 11: Trajectories of riders a week after the intervention

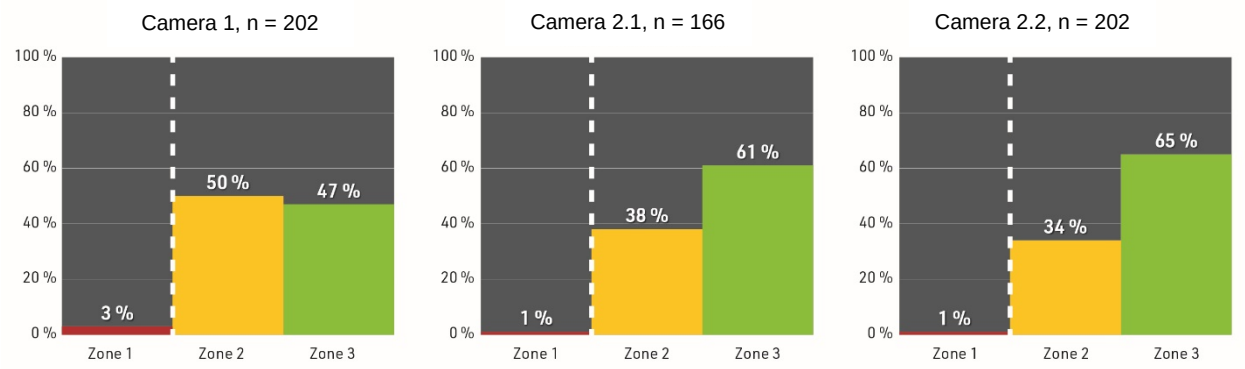

Figure 12: Trajectories of riders two weeks after the intervention

Figure 13 illustrates the development over a period of months taking the three combined bends into account and gives a very clear picture of the fact that the motorcyclists intuitively understand the new safety markings. A negative impact on other road users could not be detected.

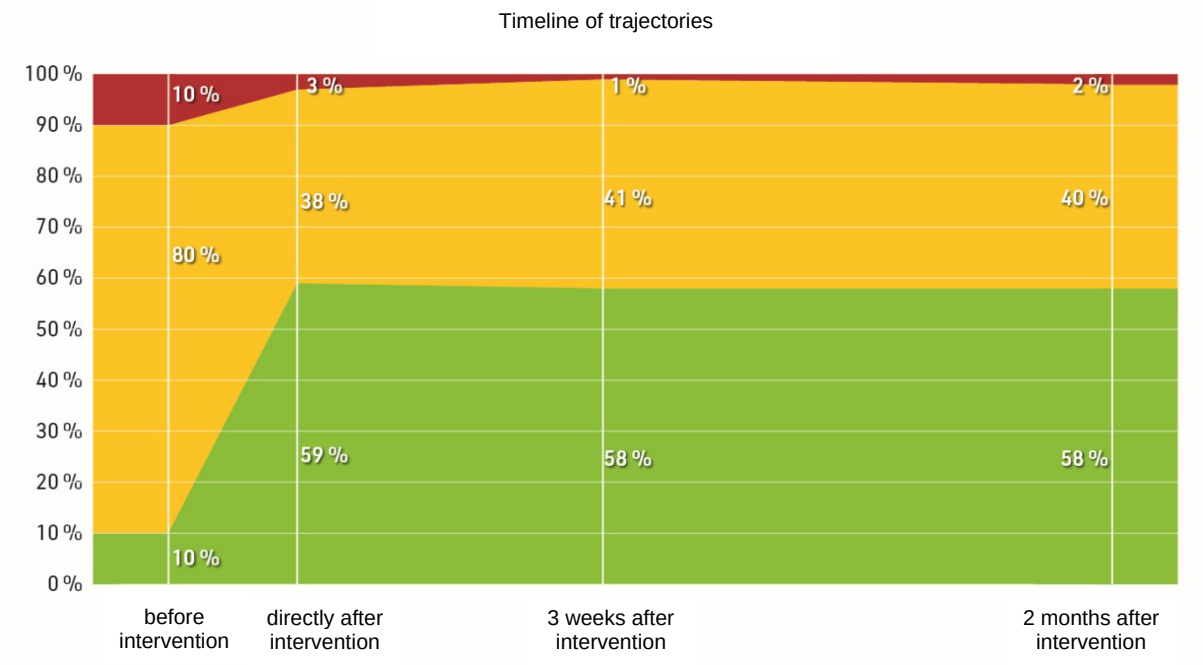

Figure 13: Timeline of rider trajectories

Effects on the occurrence of accidents.

Since the application of the markings, 2 motorbike accidents have occurred on the N25, once outside the marked bends under the influence of alcohol and one in a right-hand bend. There have been no known motorbike accidents on the other routes since then.

Other measures

To increase awareness of the road marking measure, additional information signs (Figure 14) were erected and repeated on the marked routes. Additional signage on the routes at the main border crossings and then in 2019 the dynamic warning signs on the motorway were also used. Additional checks by the Luxembourg police during the summer months were carried out and the mobile radar units were set up on the main motorcycle routes in the north of the country.

Figure 14: Warning sign "Marquage de sécurité" (Safety warning)

5.3. Criticism and complaints

There has been criticism, especially before the measure was introduced. There are no known complaints after the markings were applied. More communication and media presence might have helped, but fear of the unknown can only be changed through self-experience. The Luxembourg drivers knew the routes and the most affected foreign drivers who only come to Luxembourg for a short holiday were and are difficult to reach. After on-site inspection and driving the routes, no one complained or complained that they had slipped/skidded on them.

One feedback from a president of a motorbike club should be mentioned: He rode the route with his daughter and her friend, both beginners, without prior explanation or discussion. Both understood the "message" after 2 bends. As of today, about 50 bends in the north of Luxembourg are equipped with the markings. 1 motorbike track could not be equipped. In the meantime, the road markings have been applied to the two routes of the rider training centres and are part of the training of all novice motorcyclists in Luxembourg. During the 2022 Tour de France, similar markings could also be seen on the Swiss stage.

6 Digression: curve cutting on right-hand bends

If one interprets "corner cutting" in the sense of an incorrect trajectory in connection with inappropriate driving speed and lean angle anxiety, then one can also speak of "corner cutting" on right-hand bends.

Specific areas that can lead to accidents even without oncoming traffic are so-called "dog bends". These are bends that become tighter as they progress; they are usually dangerous as right-hand bends where, on entry into the bend, one cannot see the entire curve. The motorcyclist chooses the driving speed on the basis of what he can see on the approach and what his personal lean angle tolerance allows. If the curve then becomes tighter, the speed is too high, and the lean angle cannot be increased. This phenomenon is so mentally intense that motorcyclists end up on the left side of the road without regard for any oncoming traffic or crash after "emergency braking". In such cases, ABS only helps if it can cope with the given lean angle.[2] In the accident statistics, these accidents can be seen as a coming off the road to the left on a right-hand bend, as a "fall from the vehicle" and, of course, as collisions with oncoming traffic.

[2] A fully cornering-capable anti-lock braking system was first available from Bosch in December 2013, installed on the KTM 1190. This "MSC" (motorbike stability control) works at all lean angles. Conventional ABS can usually cope with lean angles up to about 20 degrees. Without ABS, uncontrolled braking almost always leads to a crash.

It would seem obvious that a danger sign "Dangerous right turn" should solve the problem. In fact, however, experience has shown that the danger sign alone usually does not change anything in terms of accidents involving motorcyclists. There are no known scientific studies on the exact cause of this. However, the explanation seems likely to be that a dangerous bend is precisely what the rider is looking for - dangerous, yes, perhaps, but only really for other road users, not me. There is no patent solution for this dangerous situation. In Lower Austria, a danger sign was used on a trial basis that is not standardised in the Austrian Road Code (Figure 15). A second example of such a bend can be found in East Tyrol just before the top of the Stallersattel pass. There, even a very conspicuous warning had no significant effect (Figure 16). In some places, notices on an additional sign such as "narrowing" or "getting narrower" are used. Using ground markings, on the other hand, is difficult. In such bends, it would be necessary to reduce the approach speed of motorcyclists, and as the tests on left-hand bends showed, the ground markings discussed here had no significant speed-reduction effect. Trying to compensate for a narrowing curve at the beginning of the bend with the use of road markings would be associated with "pushing" the motorcyclists to the inner edge of the bend. This has a negative effect on visibility, and the space available is naturally also limited. If road markings are installed in such bends, then this can only have the general aim of increasing the attention of motorcyclists. One makes use, as it were, of the fact that the ellipse from the left-hand bends is known as an indicator of motorcycle-specific danger. It can also be assumed that the unusual markings - even if the motorcyclists are not familiar with them - trigger scepticism and motivate them to slow down. Observations suggest that this is the case, but there is as yet no solid scientific evidence (Figure 17).

Figure 15: Traffic signs in the Höllental

Figure 16: Stallersattel, very conspicuous marking

Figure 17: Road markings on a right-hand bend

7 Discussion

The use of road markings to influence the trajectories of motorcyclists has proven successful in all its applications. In some cases, the effects have been formally investigated scientifically, in others only informal feedback is available. Negative feedback or even accidents caused or facilitated by the markings have not been reported. The target group also has a positive attitude towards the measure. On the one hand, this has been shown by surveys of motorcyclists after riding on routes with road markings. On the other hand, the initially vehement rejection of road markings on the part of individual organisations of motorcyclists has now largely fallen silent.

7.1. Transfer of measure to regular operations

The transfer of this hitherto experimental measure to regular operations thus appears to make sense. Even if, as mentioned above, it is not required in Austria, it would make sense, due to the positive scientific assessment, to integrate the markings presented here in the Road Markings Ordinance and in the relevant technical guidelines. Currently, RVS 2.2.42 "Recommendations for improving safety for motorbike traffic" is being revised. This is a technical standard of a recommendatory nature, which is being prepared and published by the Road-Rail-Traffic Research Association (FSV). The standard is expected to contain a general description and some application examples. Publication is planned for 2023. As a technical standard, this first official documentation facilitates application. At the same time, work is also being done on comparable technical standards in other countries.

7.2. Preferred shape of the markings

The W-shaped markings (Figure 18) proved to be very effective against accidents but have the disadvantage that they resemble barrier (no-go) surfaces and can thus be misinterpreted. Ellipses proved to be a better option than bar markings in the first evaluation, but the second investigation showed that the effect on trajectory is very similar. Bar markings have the advantage that they are known from prior use e.g., in front of zebra crossings - as is the desired behaviour. Ellipses seem to increase attention to a higher degree. It can be concluded that they are more suitable for applications where other measures (e.g., speed limit, no overtaking, danger signs, guide angles) have already been used to no avail.

7.3. Need for prior information

The question of whether it is necessary to announce the use of the markings via traffic signs was also discussed. When the W-shaped markings were used in Slovenia, the correct behaviour was shown on a large-format board. (Figure 18). At the Großglockner, a similar approach was taken; for the applications in Lower Austria, the danger sign "andere Gefahren" (other dangers) was used with an additional sign "Sondermarkierung" (special marking). In Luxembourg, an announcement was made at the state border. In all other applications, specific announcements were dispensed with. In the initial stages, an announcement was a precautionary safety measure. In the meantime, however, it can be assumed that the significance of the markings is generally known among motorcyclists. The self-explanatory nature and the positive effect as well as the absence of any negative experiences also make an announcement no longer seem necessary from a legal point of view - as the duty of care of the road maintenance authority.

Figure 18: Announcement/explanation in Slovenia

7.4. Film vs. paint

The studies showed that the use of film material has some advantages. You can apply the film on without gluing them, check the visual impression, test drive it and then make corrections to the position. The application is very easy and can be done by one person. The markings can be driven on immediately after installation. The processing of a bend can normally be completed within half an hour. The durability of markings made of film material is normally at least three years. Film is unsuitable for heavy traffic, which massively reduces its durability. Heavy winter service (e.g., snowploughs with snow chains) also reduces the durability. On the other hand, markings made with conventional paint have not caused problems in any application so far.

7.5. Cost-benefit calculation

The application of road markings is extremely cost-effective, especially compared to the cost of accidents: to tape a bend with film, one usually gets by with material worth less than 1,000 euros, and the use of paint material is even cheaper. Even if one rounds up generously after distributing these costs over a three-year lifespan, one would only have to prevent one lightly injured person every 80 years or one seriously injured person every 1000 years and would still have a positive cost-benefit ratio (for macroeconomic crash costs see Sedlacek, Steinacher, Mayer & Aschenbrenner, 2017).

7.6. Further need for research

Further studies on the effectiveness itself are needed. Unfortunately, the great success of the measure also means that the low accident figures after the intervention make statistical proof of effectiveness impossible. One can include further bends in the evaluation or extend the observation period to broaden the calculation basis.

The same applies to noise abatement. Here, local successes have been achieved, at least in the short term. Whether the improvements for the residents are sustainable should be scientifically investigated.

There is currently too little evidence regarding the use of the material. Neither for film nor for bends processed with paint has there been any negative feedback so far.

As mentioned, the markings should not be used too extensively. However, it seems appealing to educate motorcyclists to select a safe trajectory by marking several bends on a kind of "teaching route". There is a risk, however, that this concept will not work and that instead a habituation process will occur that will reduce the effect of the markings on the particularly dangerous bends. However, such a concept could be tested under appropriate scientific supervision.

Occasionally, right-hand bends have also been provided with markings in previous studies and their effect investigated. It goes without saying that the effect on right-hand bends must be different because it is not possible to influence the trajectory to the same extent as on left-hand bends. There are clear indications that there is another mechanism of action, which consists in the fact that the elliptical markings known from left-hand bends are perceived as a symbol of danger on right-hand bends. This would be a promising hypothesis for further research.

As an additional finding, the presumption that motorcyclists do not take general danger signs seriously was confirmed - to a large extent in the preparatory work for the studies. Ordinary danger signs and regulations often had no effect. In contrast, the road markings studied clearly communicate that their message is aimed at motorcyclists, and this may even be the hidden reason for their effectiveness. In this respect, it is in any case obvious that a motorcyclist-specific message should be conveyed, as in Figure 15. By adding a pictogram of a motorbike to other traffic signs, this aim could also be achieved using other signs. This hypothesis should be investigated further too.

Finally, despite the great progress made by the work commissioned by the German Federal Highway Research Institute (bast), it has not yet been proven that "lean angle anxiety" is actually an anxiety in the pathological sense.

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