Using Car2X Data for Friction Potential Prediction

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Abstract

In this paper the requirements of a friction potential prediction system for autonomous vehicles are discussed. Accelerations used by human drivers and accident statistics are evaluated to define these requirements. It will be shown that driving without accounting for the friction potential should be possible under dry and wet road conditions, but special cases such as snow and ice on the road, risk of aquaplaning or slippery surfaces have to be known with a sufficient preview in order to adapt the driving strategy. The required preview distance cannot be covered by on-board sensors. Therefore, possibilities of using external data sources and Car2X communication are discussed.

Keywords: friction, accident statistics, Car2X, weather data

1. Motivation

The friction potential of a vehicle is the physical property which defines the maximal lateral and longitudinal acceleration capabilities. Estimating this property is difficult, because it depends on many properties of the tire, vehicle, road and an eventual intermediate layer such as water, snow, ice or dirt. Besides the tire, which is the only parameter the vehicle owner has control over, the intermediate layer has the largest influence on the friction potential.

In recent years, research in friction potential estimation methods concentrated on applications in advanced driver assistance systems and vehicle control systems [17, 21]. ADAS[1] can use knowledge of the friction potential in various ways, such as adapting the safety margin when using a speed controller or changing intervention times of emergency systems. For example, an automatic emergency braking system has to initiate the full braking manoeuvre earlier on a low friction surface than on a high friction surface. In such situations an accurate estimate of the maximum friction potential, right before it is used, is needed. Requirements for an emergency braking application are derived in [22]. The available estimation time and needed accuracy hereby depend on the available friction and driving velocity. For example, a friction estimation with a required accuracy of less than 0.15 at typical motorway speeds above 80 kph and a reference friction value of 0.8 is derived. For slower speeds higher estimation errors are allowed. Assuming instantly available maximum deceleration, the required intervention distance (equal to the stopping distance) on a high friction surface ($\mu = 0.8$) and at an initial speed of 70 kph is around 24 m. For a low friction surface ($\mu = 0.1$) like ice with the same initial speed the derived preview distance is 192 m. In the rare cases of these emergency situations, the system needs to decide, when to initiate the full braking manoeuvre.

In contrast to these emergency situations autonomous vehicles require continuous knowledge about the friction potential for two planning tasks. In the route planning stage, potential dangerous spots can be avoided by planning a different route. In the trajectory planning stage, it has to be ensured, that the friction potential is high enough, so that the planned trajectory can be followed. Trajectories reaching the maximal friction are probably only required in rare emergency situations.

These planning stages for normal driving have significantly different requirements for estimation accuracy and and preview distances. For the route planning stage the preview depends on the operating area. In order to decide, which route is the safest, information about each possible route has to be available. Depending on the route distance, this also requires an accurate preview ranging from several minutes to hours.

The trajectory planning stage can require a preview of over 100 m. Figure 1b shows examples of different preview requirements with the assumption, that the speed of the vehicle has to be reduced prior to the change in friction in a way that the stopping distance on the low friction is the same as on the higher friction surface. In order to conduct this speed change, a moderate deceleration of $a_{mod} = 1.5\,\mathrm{m/s^2}$ has been assumed. As an approximation for the calculations it has once again been assumed that the required deceleration is available instantly. The target

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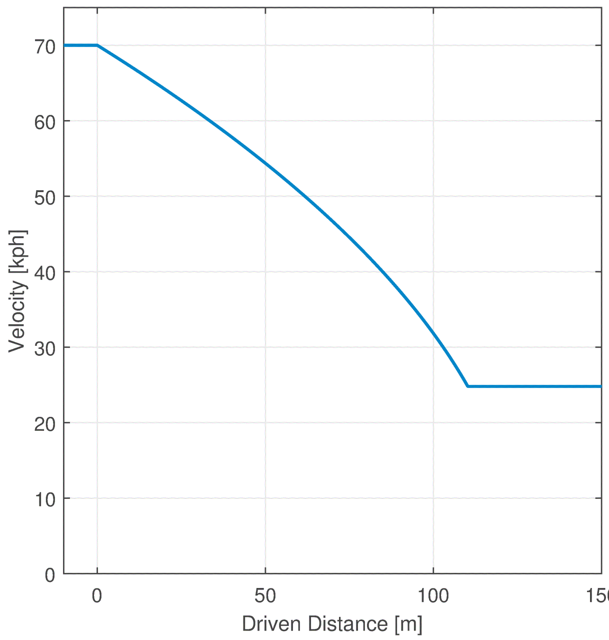
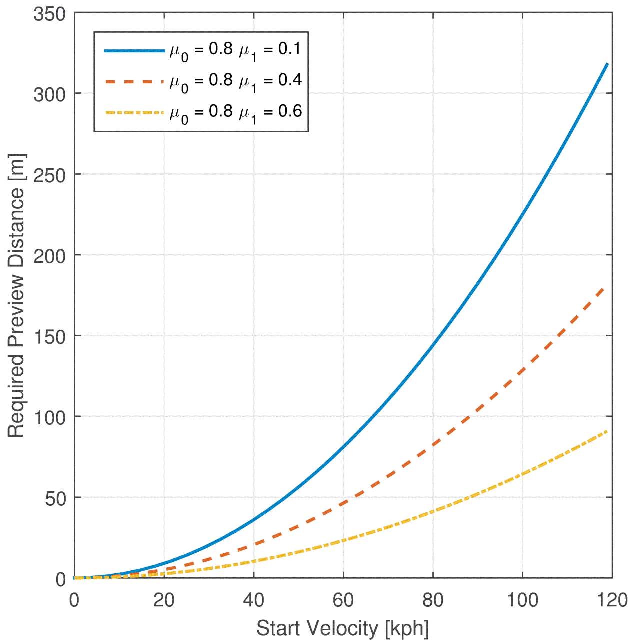
[1] Advanced driver assistance systems



(a) Example velocity adaption for ice spot ($\mu = 0.1$) on high friction road ($\mu = 0.8$)



(b) Required preview distances for different friction changes

Abbildung 1: Required preview distances for speed adaption.

velocity can be calculated by

$$v_{target} = \sqrt{v_0^2 \frac{\mu_{target}}{\mu_0}} \tag{1}$$

and the required distance for this speed change with

$$s_{preview} = \frac{(v_0 + v_{target})(v_0 - v_{target})}{2a_{mod}} \tag{2}$$

Figure 1a shows an example of the velocity adaptation with this described strategy. In this scenario the vehicle is driving with a velocity of 70 kph on a road with a friction potential of 0.8. At least in 110 m distance from an ice spot on the road, the friction potential prediction system informs the vehicle about the ice spot on the road. The vehicle starts decelerating slowly until it reaches a speed of 25 kph, which is the velocity deemed safe for icy roads. This scenario is a worst case situation, since icy roads should already be avoided in the route planning stage.

In order to derive a better understanding of requirements for a friction estimation system for autonomous driving, in section 2 the driving behaviour of human drivers is analysed and in section 3 accident statistics are evaluated to discover potentially dangerous situations. Finally, in section 4 potential sources of infrastructure data are evaluated, whether they can help detect dangerous situations identified in the previous sections.

In section 2 and 3 the data of human drivers is used. There are two main reasons to evaluate human driving behaviour. First, at this time no fleet data of autonomous vehicles is available and second, autonomous vehicles will drive on the same roads as human drivers. Thus, they should behave similar to human drivers.

2. Friction Requirements for normal driving

A good starting point for evaluating normal driving requirements is looking at naturalistic driving data. In [18] the baseline data of a 100 car naturalistic driving study conducted in the USA was evaluated to identify risky driving behaviour. 88.8 % of this baseline data was recorded during clear conditions, 10.9 % during rain and only 0.3 % during snow conditions. Thus, it can be assumed that the data is dominated by driving on high friction surfaces. The analysed data shows that longitudinal accelerations above 0.6 g occur very rarely. For drivers categorized as safe drivers only 0.3 % of all longitudinal positive accelerations above 0.3 g are also above 0.6 g, resulting in around 150 occurrences per million vehicle miles travelled. The results for deceleration and lateral accelerations in this study are comparable with around 400 decelerations above 0.6 g per million vehicle miles and around 500 lateral accelerations above 0.6 g for safe drivers. The exact values for lower lateral accelerations and longitudinal decelerations are not given in the study, but it is visible in the diagrams, that

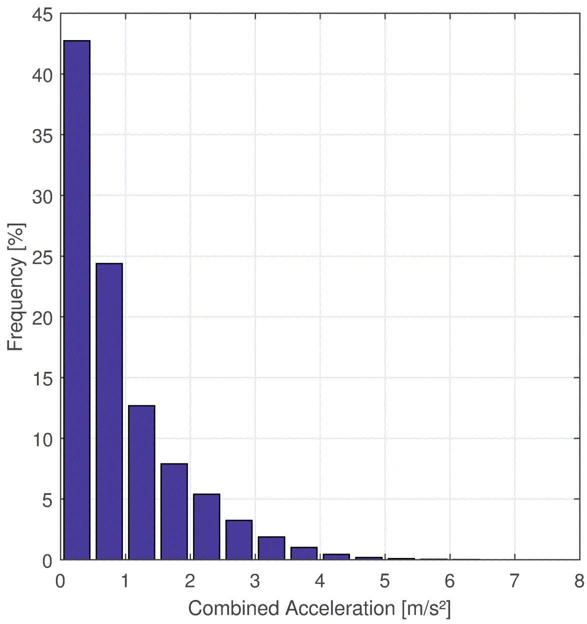


Abbildung 2: Distribution of combined accelerations $a = \sqrt{a_x^2 + a_y^2}$ based on EuroFOT data used in [3], filtered for high friction surfaces and velocities below 70 kph in 0.5 m/s^2 groups

lateral accelerations between 0.40 g and 0.49 g occur four times less than accelerations between 0.30 g and 0.39 g.

In [3] the accelerations of 15 vehicles, which took part in the EuroFOT study [1], were evaluated. The results show, that lateral accelerations above 0.2 g are almost never reached for motorway speeds. For speeds below 70 kph most lateral accelerations are below values of 0.4 g. In the longitudinal direction human drivers rarely decelerate or accelerate with more than 0.25 g. For this evaluation all measured data was used, so it cannot be disregarded that significant amounts of driving took place on low friction surfaces and thus the drivers adapted their driving style or it was not possible to accelerate harder. Therefore, the same data was re-evaluated with the limitation that only data was used for which the wiper was switched off and the ambient temperature was above 10 °C. This way snow, ice or large amounts of water on the road can be excluded and high friction conditions can be assumed. Since [3] shows the largest accelerations in the speed range below 70 kph, the evaluation was also limited to this speed range. This filtering of the data results in a data basis of above 30 000 km. Figure 2 shows the distribution of the combined lateral and longitudinal accelerations.

This evaluation confirms the relative low acceleration values recorded in the study. Less than 3 % of the used accelerations are between 0.3 g and 0.4 g and only 0.8 % are above 0.4 g. This means less than a quarter of all accelerations above 0.3 g are also above 0.4 g, which are comparable observations to those made in the previously mentioned 100 car study.

In [16] a smaller study, in which 11 test subjects drove several limited road segments containing a country road segment, a highway segment and an inner city part, also came to the conclusion that during normal driving, the drivers stayed far away from the grip limits. In this study 90 % of the measured lateral accelerations in corners with radius between 20 m and 40 m were below 5.3 m/s^2. These values are slightly higher than expected from both previously mentioned field studies. Longitudinal accelerations at green lights of the 11 test subjects have also been evaluated in [16]. Here 90 % of the accelerations were below 2.6 m/s^2.

In literature friction potential values between 0.75 and 1.02 are given for dry roads. For wet road values in ranges between 0.6 and 0.9 are published [10]. These friction values are larger than the previously discussed requirements for normal driving.

By looking at the data of the three studies and assuming that autonomous vehicles will drive similar to human drivers, it can be concluded that guaranteeing a friction value above 0.6 should cover most driving situations. According to the filtered EuroFOT data this means that in 0.1 % of the time this would not be sufficient and according to the 100 car study 1100 acceleration events (lateral and longitudinal) would not be covered by this guarantee. The number of occurrences where accelerations above 0.6 g are used by human drivers is still significant. An overall conservative trajectory planning should limit these situations, keeping in mind that emergency situations may require higher decelerations.

3. Identifying dangerous situations

In the previous section it was shown that friction values below 0.6 are sufficient in over 99.9 % of the driving situations. It was also assumed based on published friction measurements, that the available friction on dry and damp roads is in most cases above this value. Despite of these conclusions accident statistics show, that there is a significant number of accidents caused by insufficient friction.

In [26], two different GIDAS[2] studies were conducted to analyse accidents on low friction surfaces. In the first study accidents caused by unpredictable low friction events were compared to accidents on dry roads. The definition of unpredictable low friction used in this study was, that the causes of the accidents were aquaplaning, ice or black ice and the road condition changed suddenly, so that the driver was unable to react to this change. Of over 27 200 accidents with damage to persons in the database only 129 have been caused by low friction. These are only 0.5 % of all accidents. 78.1 % of the accidents took place on ice, while 14.5 % were caused by aquaplaning. The rest of these

[2] German In-Depth Accident Study: A Database containing reconstructed accidents with damage to persons from the areas Dresden and Hannover

accidents are caused by hail or snow banks. Since the study is limited to accidents caused by unpredictable friction the study shows that over 70 % of the accidents in this category happened during periods without current precipitation.

In the second study, all accidents related to a friction reduction below 60 % of the nominal friction have been included. 981 of 29 500 accidents fall into this group. These are about 3.3 % of the included accidents. It has to be noted that low friction is not the cause of all these accidents but only a contributing factor. Over 50 % of the accidents took place during no precipitation, 23.8 % during rain and 18 % during snow fall.

According to the Statistisches Bundesamt[3] in 2015, 12 869 of 305 659 accidents with damage to persons due to slippery road conditions were registered in Germany[8]. These are 4.2 % of all accidents with damage to persons. In additional 3.7 % of accidents reduced friction due to rain or ice contributet to accidents. Since at least the sum of both, 7.9 % of the accidents, are related to slippery roads, the number is significantly higher than the 3.3 % of accidents related to reduced friction in the GIDAS study. This could have several reasons. Either the size of the data base is not large enough or the included regions do not represent the climate in Germany well enough. Another possible reason is that friction accidents may also happen, when the friction is reduced to less than 60 % or the conditions to classify an accident as caused by low friction are different. According to the data of the Statistisches Bundesamt 10.9 % of all accidents are related to slippery roads due to rain or snow.

In the published data the weather conditions snow and ice caused 4974 accidents, while rain caused 6362 crashes. Two additional drivers of accidents, not yet discussed, were road contamination and the road itself. 1553 accidents are caused by contamination of the road and 1200 by the condition of the road.

In the USA, according to [2] 22 % of all vehicle crashes are weather related. 16 % of all crashes took place on wet pavement, and 7 % on snow or ice surfaces. In [33] many different accident studies related to weather conditions are compared with some interesting results. In most of the examined studies no differentiation between the accident causes reduced friction and reduced visibility were made. Many studies find a positive relationship between rain events and accident rates. But it is has also been noted that in some Mediterranean countries during heavy rain the accident rates were actually reduced. The assumption of the authors is that the drivers drive with additional care, because rain situations are quite unusual in these countries.

According to [32], the average freeway speeds are reduced by 5 %-6.5 % on wet roads compared to dry conditions in Virginia, USA. In the study conducted in [29], an average speed reduction of 3.7 % was observed, while [20] found reductions from 95 kph on dry pavement down to 85 kph on wet pavement on an interstate. In Germany, researchers observed a speed reduction of around 10 kph on the motorways in wet conditions [7] compared to dry conditions. Since the friction reduction between dry and wet roads is in the order of 20 % the average speed reductions are not enough to counter this effect. Most studies speculate that the speed reduction is due to changes in visibility and not friction. For higher speeds, which are typical on motorways, an additional risk of aquaplaning arises if the drainage capacity of the road is unfavourable. In these cases friction can be reduced to similar low levels as on ice, which would require an even increased speed reduction. During snow and ice conditions the average driving speed adaptation seems even more inappropriate. In [20] the authors observed a speed reduction of around 20 kph was found in snow/ice conditions. In Finland, the effect of displaying a slippery road sign during winter conditions resulted in a speed reduction of around 2 kph at locations with average speeds of 90 kph. The average speed reduction due to adverse weather conditions was observed with around 5 kph.

The accident statistics show, that a significant amount of accidents happen due to rain or snow events. While less than 5 % are caused by the low friction values, it appears that reduced friction contributes to up to 20 % of all accidents. The large difference between the number of accidents on unpredictable low friction, with 0.5 % according to GIDAS, and the significantly larger number of accidents with a reduced friction potential contributed to, with 3.3 % according to GIDAS and 7.9 % according to the Statistisches Bundesamt, shows that an adaptation to lower friction values is required. Possible adaptation strategies are to reduce the driving speed, increase distances to other road users or postpone the drive.

An autonomous vehicle without any friction information cannot adapt its driving style and is at a higher risk of exceeding the available physical limits. While many of the weather related accidents could be avoided by overall defensive driving, an increased risk of planning trajectories that cannot be followed remains. Weather conditions like rain and snow/ice mainly contribute to the accident statistics but dirt and overall poor road quality seem to have additional influence.

4. Car2X data sources

Car2X technology allows cars and infrastructure to communicate with each other over longer distances. There are several possible operating models, which can be employed in Car2X communication. The vehicles in a certain area can communicate directly with each other, dedicated infrastructure like traffic lights [30] can communicate to the vehicles or the vehicles can communicate with a central service, which combines lots of external data sources and fleet data and communicates all required information to the vehicle.

[3] Federal Statistical Office

While the technology is available, defining useful data for exchange between the vehicles is still an ongoing process. In the basic set of applications for intelligent transport systems [12] use case description for road hazard warnings in the case of precipitation and low road adhesion are included. Low stability areas caused by ice, snow, oil or wind are listed as examples. In [13], the detection of black ice by several vehicles is used as another example. While this information will help recognizing some of the dangerous situation, filling these warnings with content is still an open question. In case of the black ice warning, at least some vehicles need to experience the friction limit and communicate this to the surrounding vehicles. As was shown in section 2 higher accelerations are almost never used, so that only the very low friction situation of ice can be discovered this way. Information about a limit of 0.6 will not be available in most situations. An additional problem of direct Car2Car communication is, that a significant number of vehicles need to be equipped with this technology [4].

A more promising approach is to use external data using a central service communicating with the autonomous vehicles. Using this kind of service many diverse data sources can be included. In the previous section it was shown, that weather is the main influencing factor for insufficient road friction. Today, weather information is available from many sources. For road friction estimation not only the global weather but very local effects are important, which need to be considered. Wet road conditions can either appear through precipitation or condensation. Besides the intensity of precipitation important quantities for measurement are the relative humidity and the surface temperature. Precipitation can be detected from rain radars or ground stations. These ground stations also deliver information about air temperature, humidity, wind speed and viewing distance. Special RWIS[4] [19] provide surface temperature, underground temperature and information about the intermediate layer on the road. All these data sources have some limitations, which need to be accounted for. These limitations are a regional and temporal gap. For example the hourly precipitation calculated by the DWD[5] [5] from rain radar images is only available with a resolution of $1\,\mathrm{km}^2$ and a thirty minute delay. Weather stations and RWIS sites deliver only local information. In Germany, the DWD provides data from about 1400 RWIS sites every 15 minutes. Weather forecasts are normally calculated on a grid with a resolution of 1 km or more. In [24], improvements of a grid reduction from a 36 km down to a 4 km grid in Northern America are evaluated. The results of this study show that increasing the resolution can improve the forecast accuracy. Increasing the grid resolution further is limited by computer resources and calculation time demands.

The actual road condition depends on many factors which vary on much smaller scales like heat conductivity and shading effects. Thus, bridges are especially prone to freezing effects [34], because the exposed surface can be cooled by winds faster than the surrounding roads. Similarly, frozen roads without solar radiation can remain critical while other parts of the road are already dry. In order to cover all these local effects, weather observations have to be supplemented by additional information. Several research projects have looked combining vehicle data with weather data.

In [28], the resolution of the precipitation measurements is improved by using vehicle fleet data. In this project an empirical relationship between the vehicle wiper speed and rain intensity is developed. In a further publication of this project [14] online calibration between sensors is discussed. This way, accurate information about current precipitation can be generated with wiper data, while wet roads due to past precipitation can be derived from rain radar data. For the dangerous aquaplaning situations not only information about the precipitation, but also geometric information about the road need to be available. The most important road properties for aquaplaning are the slope and banking of the road. In addition, geometric deficiencies like lane grooves can lead to larger amounts of water on the street. All these static properties can be included as properties in a map, which is required for autonomous driving [6]. This way, aquaplaning risk can be minimized. In addition, roads with insufficient friction due to the road texture could be marked on the map.

In [15], a fusion of available weather information and on-board sensors has been proposed. An algorithm for the camera is described, which can detect the intermediate layers dry, wet and snow with a recognition rate of over 98 %. In order to achieve larger preview distances, sharing the recognized data over a backend service is suggested. This intermediate layer information of a sufficient number of vehicles could close the temporal and local gap of the intermediate layer information provided by weather forecasts. No information about the visually hard to detect intermediate layer ice is given.

In [11], vehicle CAN bus data like wiper movement and air temperature are used in combination with RWIS data in order to set digital traffic flow signs according to the current intermediate layer. A combination of fuzzy logic and clustering of historic measured data is used to estimate the road surface temperature and wetness between RWIS stations.

In [25], similar vehicle data and data of a RWIS stations and other weather stations is used to estimate the intermediate layer as important input for a friction estimation method. In this project instead of fuzzy logic a cascade of logistic regressions is used to identify the intermediate layers dry, moist, wet and snow or ice. In combination with an empirical database containing the friction values for different surfaces a correct classification of the friction potential is possible in 98 % of the available data.

Another possibility to identify the intermediate layer is

[4]road weather information stations
[5]German weather service

to equip fleets of vehicles with special sensors to measure relevant properties directly [27].

Instead of using vehicle data to close the local gaps between weather stations another researched approach is mapping special track properties. Therefore, the heat conductivity of the road network is mapped using a technique called thermal mapping [31]. Here, the road temperature is measured with an vehicle equipped with an contact-less temperature sensor. In combination with the prevailing weather conditions, local heat effects can be mapped. In addition to the thermal mapping process a sky-view factor can be measured using a fish eye camera or approximated using the signal quality information of a GPS receiver [9]. With this property the amount of solar radiation on the road can be modelled. This kind of model is often used as decision support for winter road maintenance. Evaluation of thermal mapping based forecast shows very promising results in predicting the road temperature with accuracies of up to one degree [23], thus this kind of model seems suitable to detect the risk of ice on the road. Often, friction on roads with surface temperatures below 0 °C is no problem because the roads are sufficiently salted and gridded. In order to prevent unnecessary cautious and slow driving, information about winter maintenance operations needs to be included in a Car2X service.

5. Conclusion

Most of the time a higher friction than required for normal driving is available. It was shown that guaranteeing a friction value around 0.6 covers most of the normal driving situations. The residual risk of emergency situations requiring friction values over 0.6 can be minimized by adapting the trajectory planning to the known environment conditions.

The largest number of friction related accidents are caused by weather. In the previous section it was shown that many different external sources can be used to get information about the current road conditions. Since both weather forecasts using thermal mapping measurements and approaches using vehicle data rely on information from RWIS stations a sufficient distribution of these stations along the network and inclusion of their data in a Car2X service is required. The exact number of stations hereby depends on the terrain and amount of special constructions like bridges in the region. The temporal and local gaps of these stations can be covered by different approaches. In the introductory phase only few vehicles equipped with Car2X technology will be available. Nevertheless, research shows that data from vehicles can be used to correctly estimate the intermediate layer between weather stations. For wet roads, operating with an friction assumption of 0.6 is sufficient, if aquaplaning and insufficient road texture can be excluded. This can be done by storing the drainage capacities, profile and surface quality information of the road in the map.

While on wet road surfaces a friction of 0.6 can be assumed, ice and snow on the road requires a significant adaptation of driving style. The most important quantity for risk of ice is the road temperature. In such cases thermal mapping shows promising results. The risk of ice requires a bigger reduction in speeds than human drivers normally apply.

Thus, the combination of weather station data, special mapped road properties like thermal mapping and fleet data should provide a reliable classification of the intermediate layer. An overall conservative friction assumption during trajectory planning and a correct adaptation to the expected intermediate layer should allow autonomous vehicles to reduce the risk of friction related accidents significantly.

Friction reduction due to road contamination accounting for around 10 % of all friction related accidents remains an unaddressed problem and requires future research.

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