



In2Track3



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# GIP and EC on-track measurement results of the Western Main Line in Sweden

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## Abstract

This report documents the work carried out in investigating Gradient Index Profiles (GIPr for rail, GIPw for wheel and GIP for wheel-rail) along the Swedish Western Main Line connecting Stockholm and Gothenburg and serves as an extended and supplementary documentation to report 178508100-002 [7]. In particular, for all parts of track sections (Bandel, Bdl) including Bdl 410, 412, 416, 511, 512, 611 and 612, this report presents on-track measurement results of GIPr and GIP. The investigations include distribution functions of GIPr and GIP, grouped into three zones based on curve radii, and examine their correlations with both track and in-service equivalent conicities (EC S1002 and EC ref\_worn\_2021). Based on the findings presented in this report, combined with those in report 178508100-002 [7], a comprehensive understanding of wheel-rail geometry contact conditions along the Western Main Line has been achieved, which plays an important role when dealing with running instability issues and in establishing a systematic approach to improve passenger ride comfort.

*Keywords: Gradient index profile, equivalent conicity, rail profile, rail surface management, S1002, running stability, wheel-rail contact, GIP, GIPw, GIPr*

## 1. Introduction

As a complement to equivalent conicity (EC), Gradient Index Profiles (GIPw for wheel, GIPr for rail and GIP for combined wheel-rail) have been developed within the Swedish collaboration project “A systematic approach to improve passenger ride comfort” [1], in conjunction with the European projects In2Track2 [2] and In2Track3 [3]. The primary objective is to assist Railway Undertakings (RUs) and Infrastructure Managers (IMs) in implementing TSI requirements for EC. For definitions of GIPw, GIPr and GIP, as well as detailed studies showing the correlations between GIP and EC, see Refs. [4], [5], [6], [7].

In the report “178508100-002: Investigating gradient index profile and its corrections with equivalent conicity and rail surface management” [7], the distribution functions of GIPr, GIP and EC along the Swedish Western Main Line connecting Stockholm and Gothenburg were analysed, which demonstrated strong correlations between GIPr and EC. In addition, maintenance limit values (IL for Intervention and AL for Alert) for GIPr on tangent tracks were proposed. The manuscript included in 178508100-002 [7] was originally written for oral presentation at the 28th IAVSD International Symposium on Dynamics of Vehicles on Roads and Tracks, held in Ottawa on 21-25 August 2023. Currently, there is undergoing peer review process for publication in the IAVSD2023 proceedings. Due to space constraints, the comprehensive on-track measurement results were not included in report 178508100-002.

This report serves as an extended and supplementary documentation to the report 178508100-002 [7], presenting detailed on-track measurement results of GIPr, GIP and EC on all parts of track sections along the Western Main Line, including Bdl 410,412, 416, 511, 512, 611 and 612.

For each Bdl, we present summarised results in three figures containing the following:

- Results along track positions, including curvatures, track gauges (TG), equivalent conicities (EC), Nonlinear Parameters (NP), Gradient Index Profiles for Rail (GIPr) and Gradient Index Profiles for combined Wheel-Rail (GIP). From these results, an overall understanding of wheel-rail geometry contact conditions for each Bdl is obtained which facilitates the identification of track locations of abnormal values warranting further investigations.
- Cumulative distribution functions, probability density functions and normal probability plots for GIPr and GIP, grouped into three zones based on curve radius: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R < 10,000$  m and C) small curves with  $R < 600$  m. From these results, disparities between tangent tracks and curves as well as between different part of track sections (Bdls) may be observed.
- Scatter plots illustrating the relations of GIPr vs EC and GIP vs EC, from which GIPr behaviours at different Bdls and between tangent tracks and curves may be investigated.

All computations in this report have been performed using a specially developed in-house Matlab Rail Profile Toolbox, currently at version of No. 623 [8]. Throughout this study, various enhancements and modifications have been implemented. A list of these changes is included in the report for the convenience of a potential new updated version of the toolbox in the future.

This work is part of the project “A systematic approach to improve passenger ride comfort” [1]. This collaboration project between the infrastructure manager Trafikverket and operators SJ AB and A-Train AB, together with external partners, aims to improve the handling of bad ride comfort. The current rules and regulations are centred on safety and are often poorly adapted to handle ride comfort issues, especially for factors shared between track and rolling stock such as the wheel-rail contact conditions. The project is part of the In2Track2 [2] and In2Track3 [3] initiatives in the EU Innovation Programme 3.

## 2. Definitions for GIPw, GIPr and GIP

The Gradient Index Profile (GIP) is derived from the following four values:

- GIPwL and GIPwR: GIP for wheel (GIPw), left and right wheel respectively;
- GIPrL and GIPrR: GIP for rail (GIPr), left and right rail respectively.

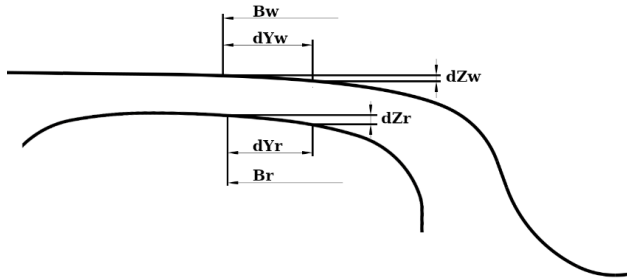


Figure 1. Parameters used in calculation of GIPw and GIPr

Using the parameters shown in Figure 1, GIPw and GIPr are defined as

$$GIPw = 100 \cdot \frac{dZw}{dYw} \quad \text{and} \quad GIPr = 100 \cdot \frac{dZr}{dYr} \quad (1)$$

where  $Bw = 750$  mm is the lateral distance of the reference point from centre of wheelset, and  $Br = 751$  mm is the lateral distance of the reference point from centre of track, assuming that the nominal track gauge is 1435 mm. Further,  $dZw$  is determined by finding the vertical position of the wheel surface point with  $dYw = 15$  mm, whereas  $dZr$  is determined by finding the vertical position of the rail surface point with  $dYr = 16$  mm. The differences between  $Bw$  and  $Br$ , and  $dYw$  and  $dYr$ , are intentional and optimized to give the best predictive power for EC.

By combining the wheel and rail gradients, GIP is defined as

$$GIP = \frac{GIPwL - GIPrL}{GIPwL + GIPrL} + \frac{GIPwR - GIPrR}{GIPwR + GIPrR} \quad (2)$$

## 3. Matlab Toolbox

An in-house Matlab Rail Profile Toolbox, currently at version No. 623 and comprising around 30 Matlab functions, has been specially developed for evaluating equivalent conicity and other related wheel-rail geometric contact functions. The development of this Toolbox stemmed from a NIM-project supported by Nordic Infrastructure Managers from Denmark, Finland, Norway and Sweden. Subsequently, the project was further developed by Dreik Ingenjörskonst AB, leading to the current Toolbox version, which is frequently used by Infranord, Trafikverket and other partners [8][9].

Throughout the study, numerous enhancements and modifications have been implemented. The major modifications are outlined below:

- Modification of the function `brpt_readkmm2.m` to align with Infranord's adoption of a new version of data format in `*kmm2` file.
- The Toolbox has been using "caching" to speed up the computational process. However, this doesn't work well for our current working conditions, as we are working

with a server where the writing of data is not permitted. Therefore, several functions are updated either by setting the usecache parameter as false or modifying the related parts of functions.

- Update of the function `brpt_itrxtsync_make.m` to ensure correct invocation of two `config*.txt` files.
- Enhancements within the function `brpt_itrxeqvcon.m`, including evaluations of EC for multi wheel profiles, extraction of parameters for rail profiles, track gauges, curvatures, GIPr and GIP, EC values at 2mm, 3mm and 4mm, among others.
- Modification of the function `brpt_gip.m` to ensure the use of correct parameters as defined in Figure 1 and determination of the track centre using the line 3 mm below the top of the rail instead of the original 14 mm.
- Addition of a function named `brpt_remove_backsteps.m` provided by Ingemar Persson to prevent computational process stops due to inappropriate use of interpolation function within Matlab.

## 4. On-Track Results

In this section, comprehensive on-track measurement results of GIPr, GIP and EC on all track sections are presented, including Bdl 410, 412, 416, 511, 512, 611 and 612, along the Western Main Line in Sweden connecting Stockholm and Göteborg, see Figure 2. While the focus in report “178508100-002” remains on the behaviour of GIPr especially on tangent tracks along the whole line, the results presented here are for each Bdl and include curves. As previously mentioned in the Introduction, the results for each Bdl are summarized in three figures, following a consistent format.



Figure 2. The Western Main Line in Sweden connects Stockholm and Gothenburg and is a 455 km long ballasted double track with 60E1 and 50E3 rail and Monoblock concrete sleepers.

## 4.1 Bdl 410: Älvsjö-Södertälje hamn

Bdl410, a part of track sections (Bandel) located between Älvsjö (Äs) and Södertälje hamn (Söd) as depicted in Figure 3, comprises a ballasted double track primarily utilizing 50E3 rail and concrete sleepers and including numerous curves with radii ranging from 300 m to 2500 m. Information from the databases BIS and OPTRAM indicates that Bdl410 has undergone various renewal activities spanning from the 1980s to the 2010s, and several rail surface maintenance actions (grinding) have been performed in recent years.

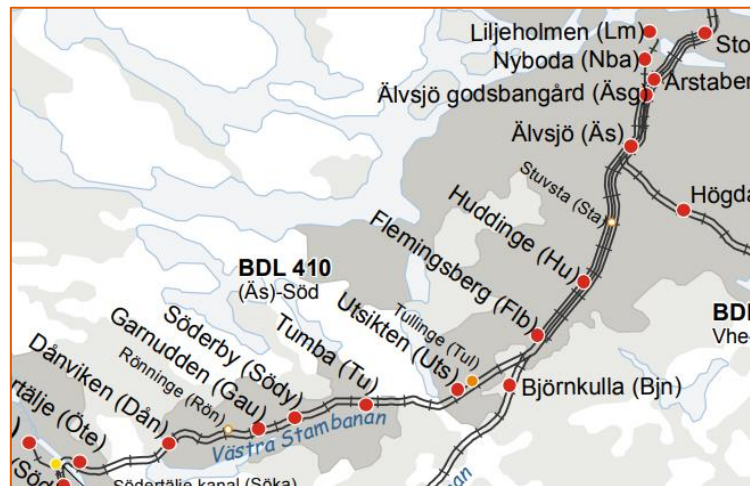


Figure 3. Bdl 410 Älvsjö – Södertälje hamn

The results presented in Figure 4 show that the wheel-rail contact geometry conditions at Bdl410N are generally good. We observe that, for majority of the track locations, both track EC with the nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref\_worn\_2021) remain well below the TSI limit value of 0.3, the Nonlinearity Parameters (NP) exhibit positive values, the values of GIPrL and GIPrR are well above the proposed Alert Limit value (GIPrAL) of 8.0, and the corresponding GIP values are well below zero. We also observe that there exist specific track locations where the values of EC ref\_worn\_2021 exceed the value of 0.3, NP values are below zero, and GIPr values fall below GIPrAL, for which further investigations will be done in our future studies.

Figure 5 summarizes the results of the cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones based on curve radius: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m. A notable difference is observed between these zones, particularly with higher mean and variance values in smaller curves.

Figure 6 illustrates scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr, to demonstrate correlations in these three zones. The predominance of higher EC values is noted in Zone A, the tangent tracks with  $R \geq 10,000$  m.

Similar observations and results for Bdl 410U are presented in Figure 7, Figure 8 and Figure 9.

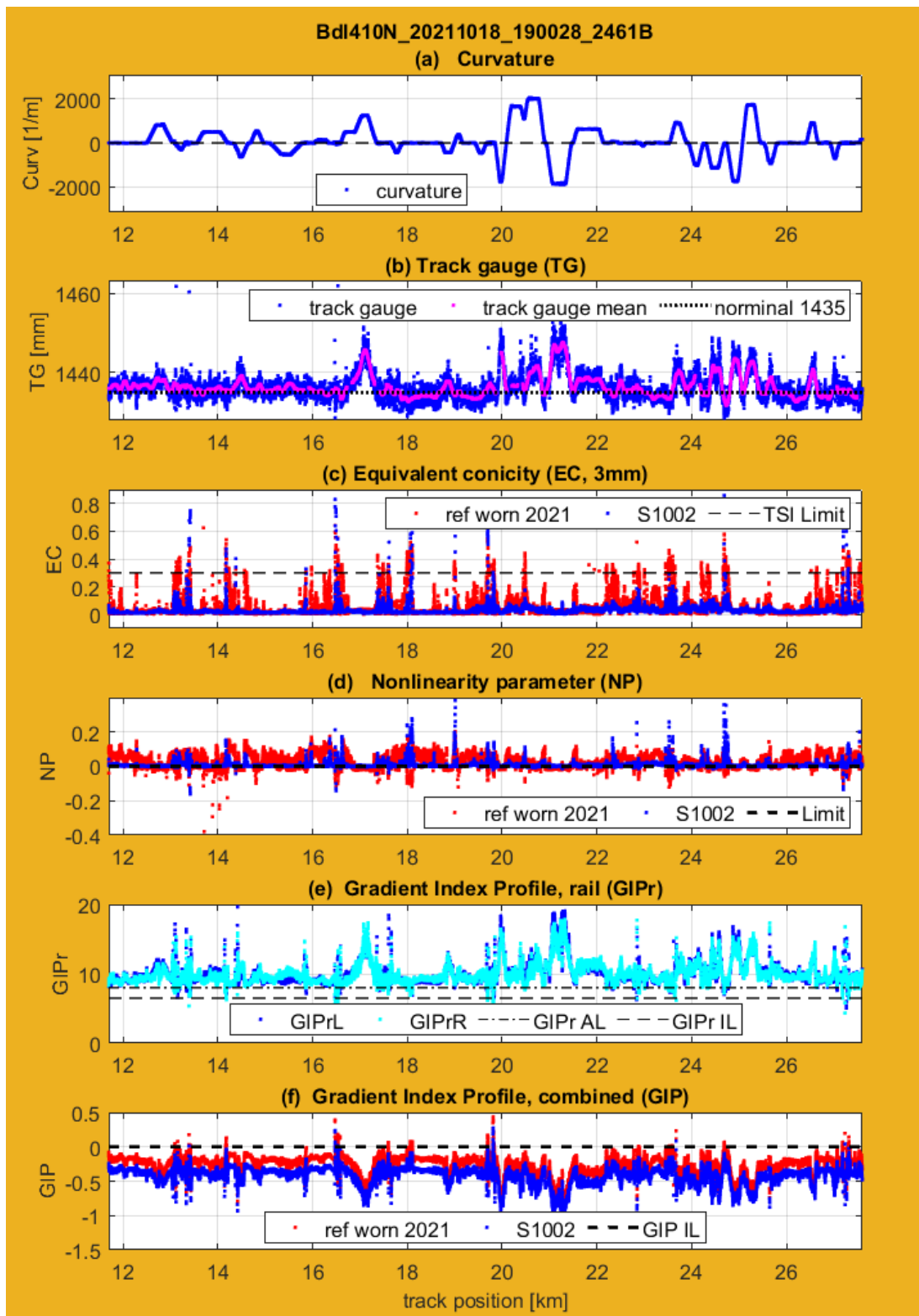


Figure 4. Results for Bdl 410N: (a). Curvature ([1/m]), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref\_worn\_2021), (d). Nonlinearity parameter (NP S1002 and NP ref\_worn\_2021), (e). GIPrL and GIPrR and (f). GIP S1002 and GIP ref\_worn\_2021.

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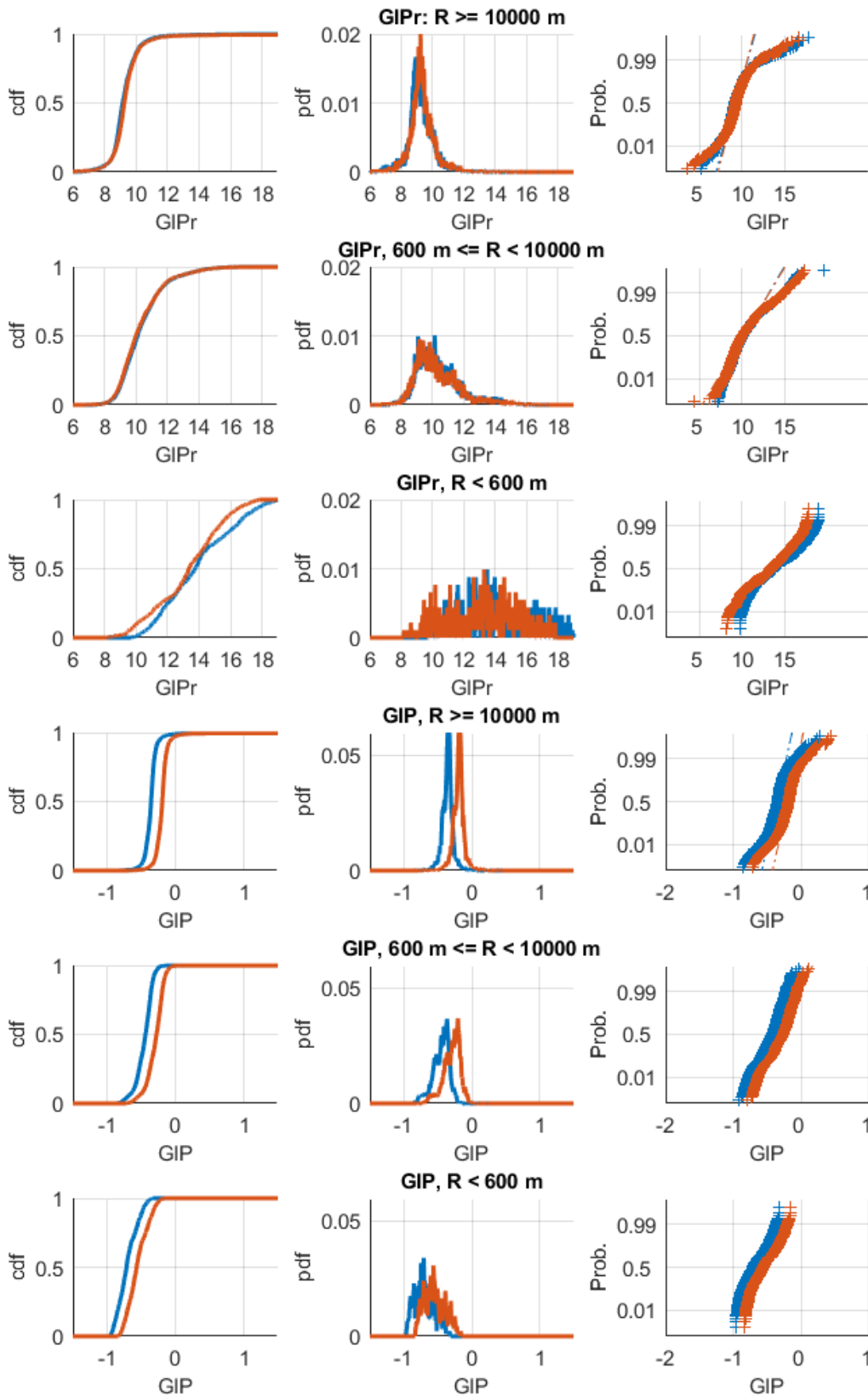


Figure 5. Results for Bdl 410N: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

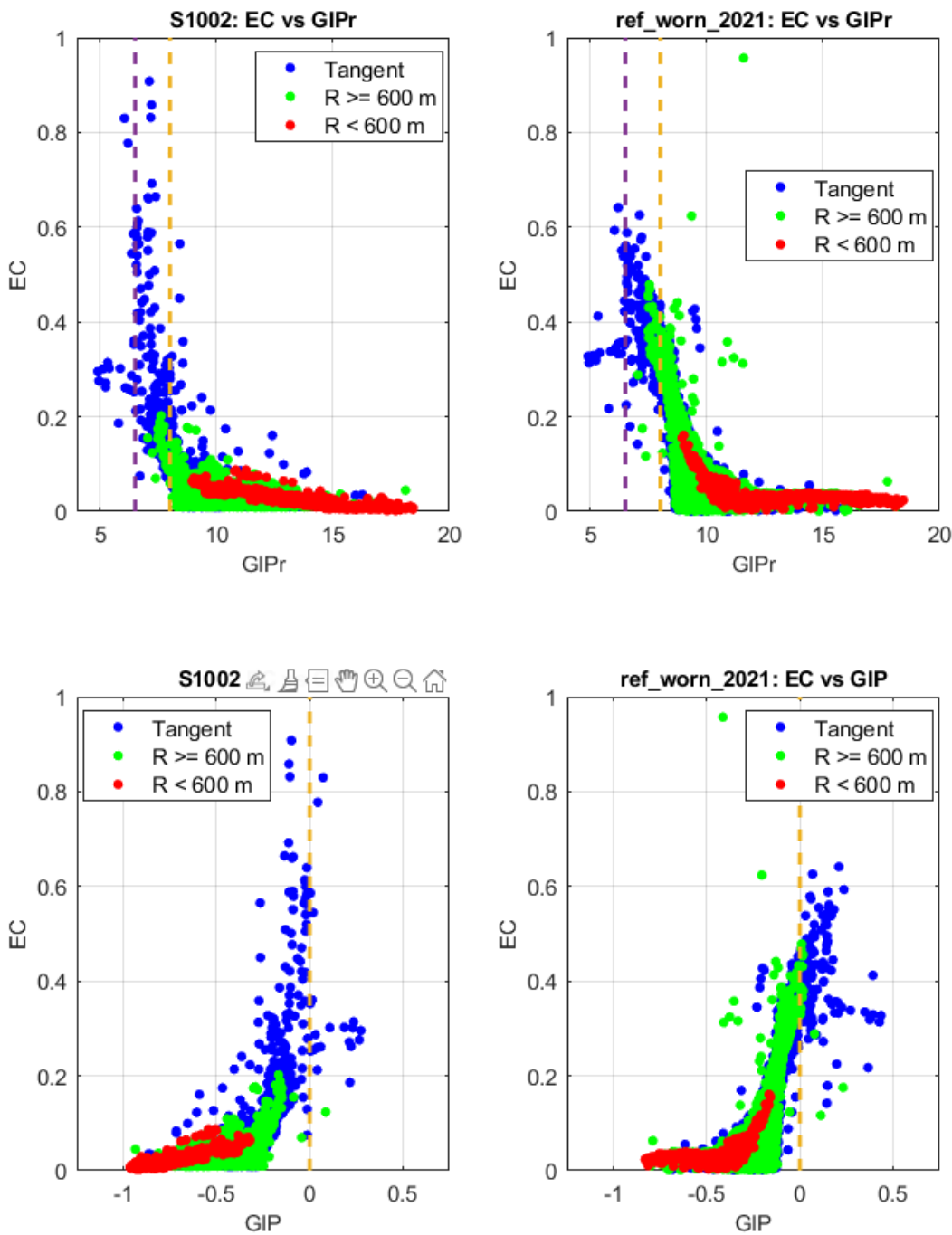


Figure 6. Results for Bdl 410N: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIP for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

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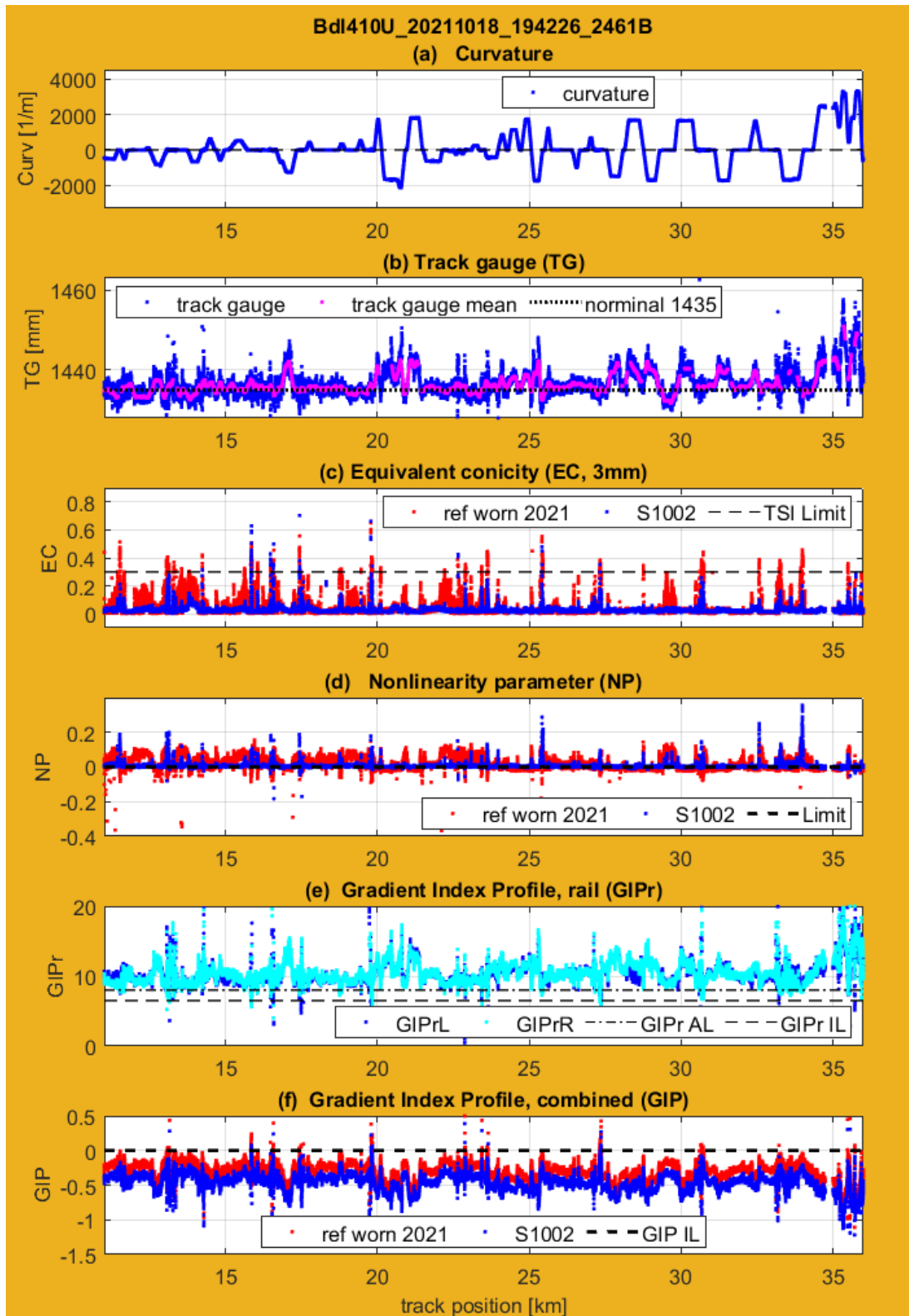


Figure 7. Results for Bdl 410U: (a). Curvature ([1/m]), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref\_worn\_2021), (d). Nonlinearity parameter (NP S1002 and NP ref\_worn\_2021), (e). GIPrL and GIPrR and (f). GIP S1002 and GIP ref\_worn\_2021.

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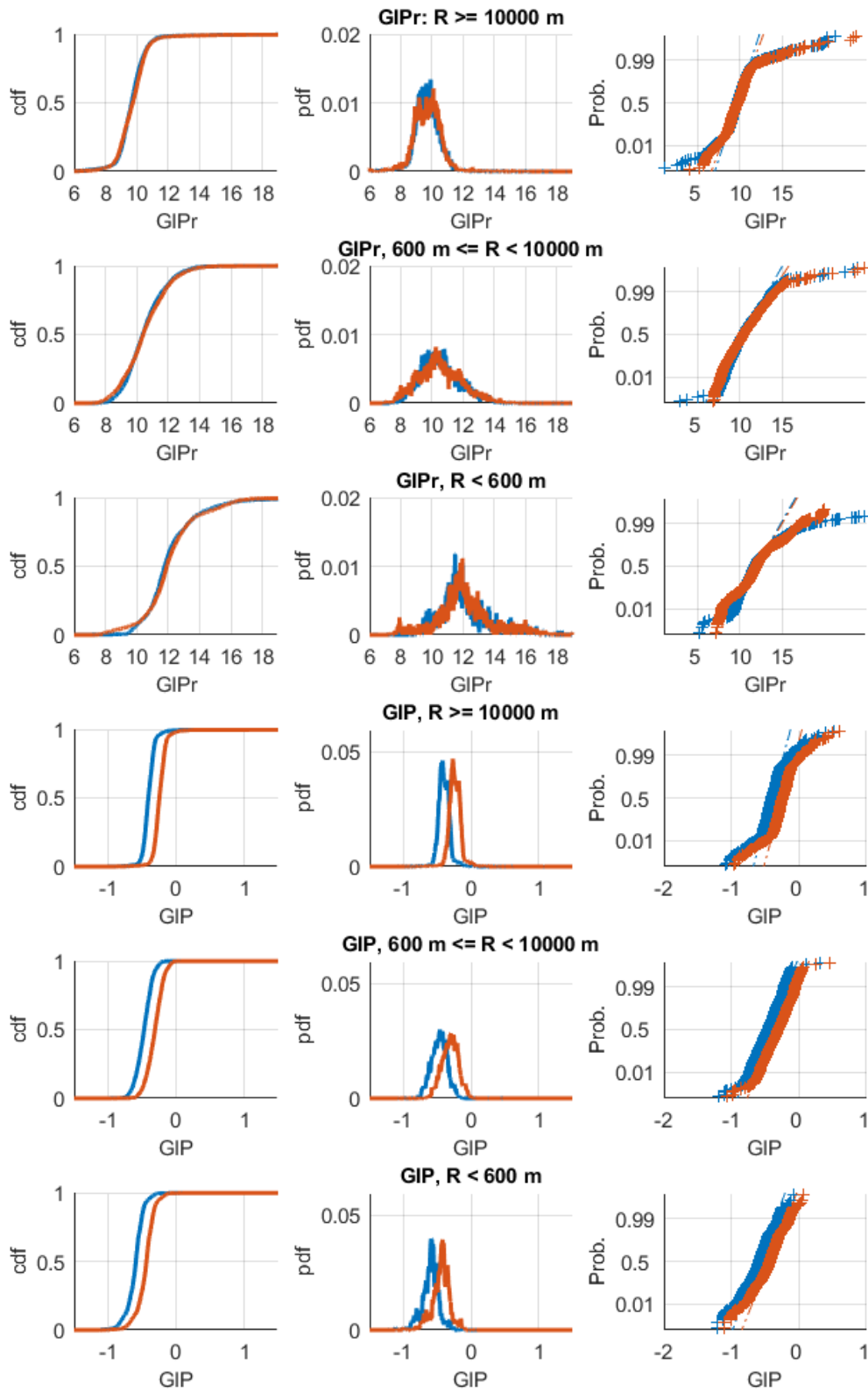


Figure 8. Results for Bdl 410U: Results for Bdl 410N: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R < 10,000$  m and C) small curves with  $R \leq 600$  m.

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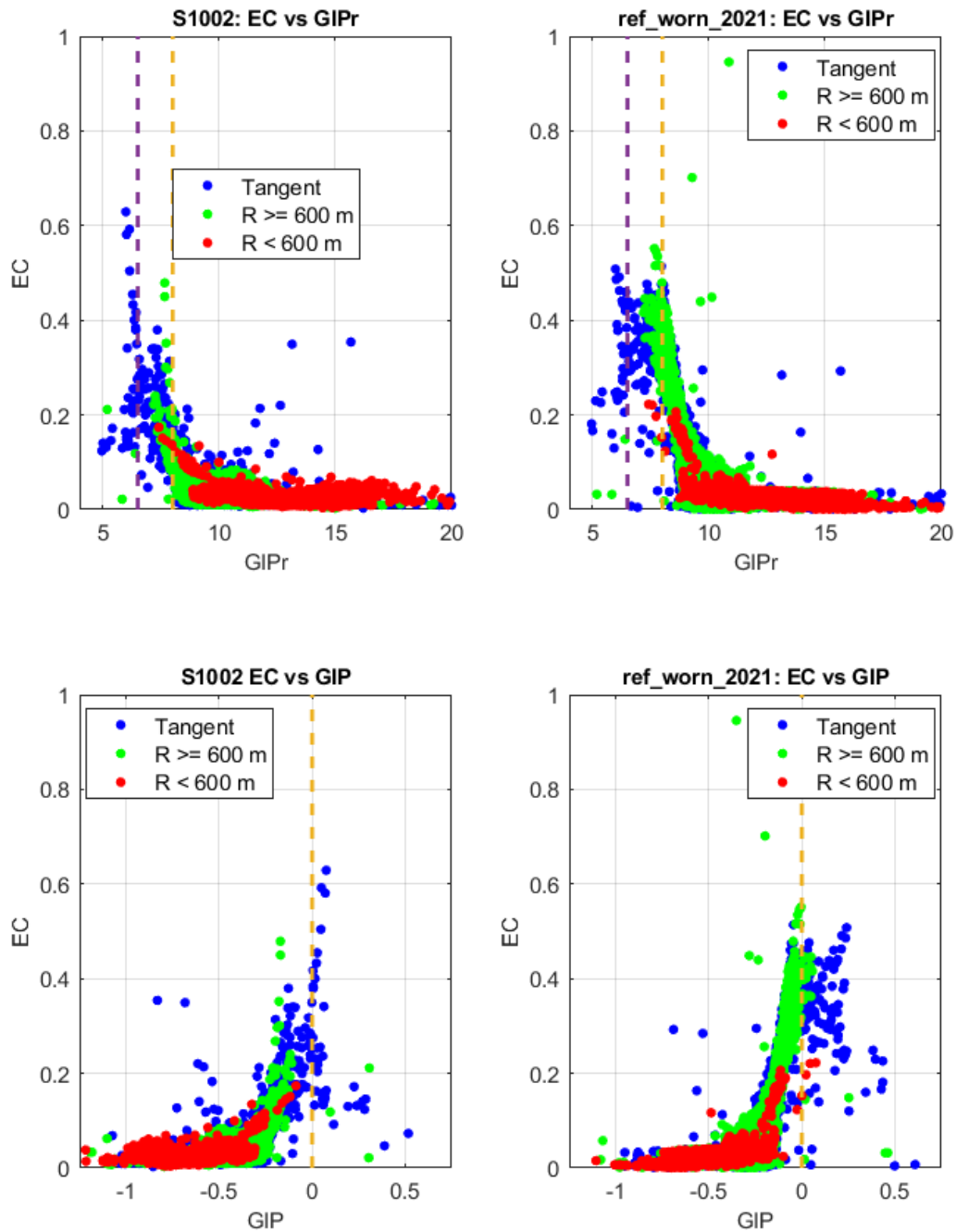


Figure 9. Results for Bdl 410N: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

## 4.2 Bdl 412: Södertälje hamn - Järna

Bdl 412, a part of track sections (Bandel) located between Södertälje hamn (Söd) and Järna, as depicted in Figure 10, comprises a ballasted double track predominantly utilizing 60E1 rail and concrete sleepers, featuring only a few large curves. Information from the databases of BIS and OPTRAM indicates that Bdl412 has undergone various renewal activities dating back to the 1990s. Additionally, recent years have seen several rail surface maintenance actions (grinding), carried out both in Bdl 412N and 412U.

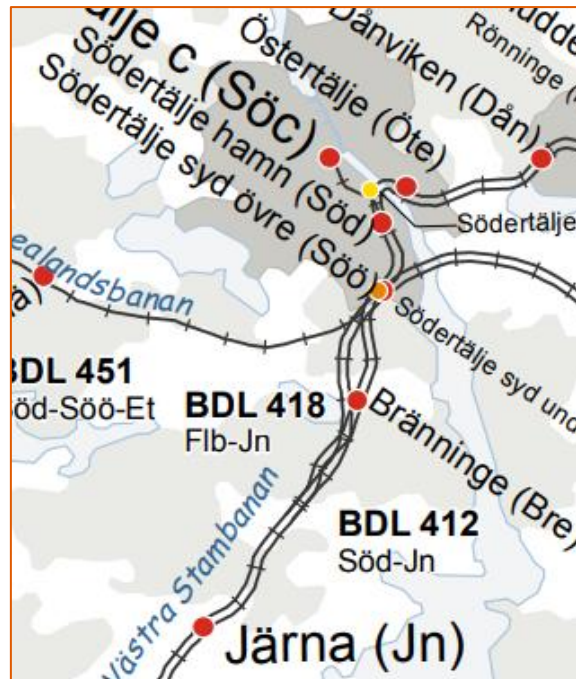


Figure 10. Bdl 412: Södertälje hamn (söd) – Järna (Jn).

Figure 11 summarizes the results for Bdl 412N, including curvatures, track gauges (TG), equivalent conicities (EC S1102 and EC ref\_worn\_2021), Nonlinearity Parameters (NP), Gradient Index Profiles for Rail (GIPrL and GIPrR) and Gradient Index Profiles for combined wheel-rail (GIP S1002 and GIP ref\_worn\_2021). Few locations show EC ref\_worn\_2021 values exceeding 0.3 and GIPr values below GIPrAL, warranting further investigation.

In Figure 12, cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP are summarized. Notably, there's a marked difference between Zone A and Zone B, while no results are available for Zone C.

Figure 13 displays scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr. Similar trends are observed in Zone A and B, indicating strong correlations between EC and GIPr/GIP.

Similar observations and results for Bdl 412U are depicted in Figure 14, Figure 15 and Figure 16.

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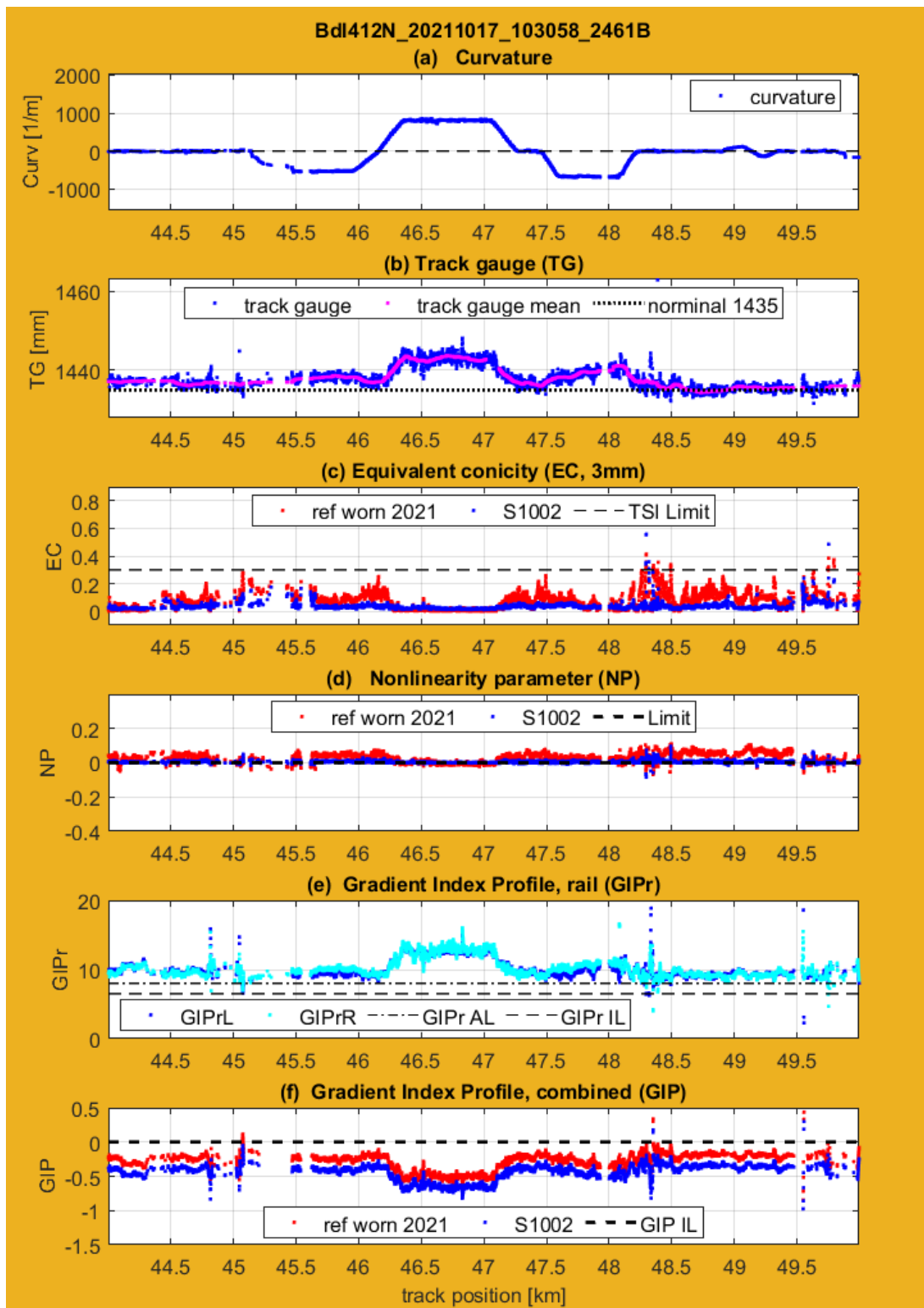


Figure 11. Results for Bdl 412N: (a). Curvature ([1/m] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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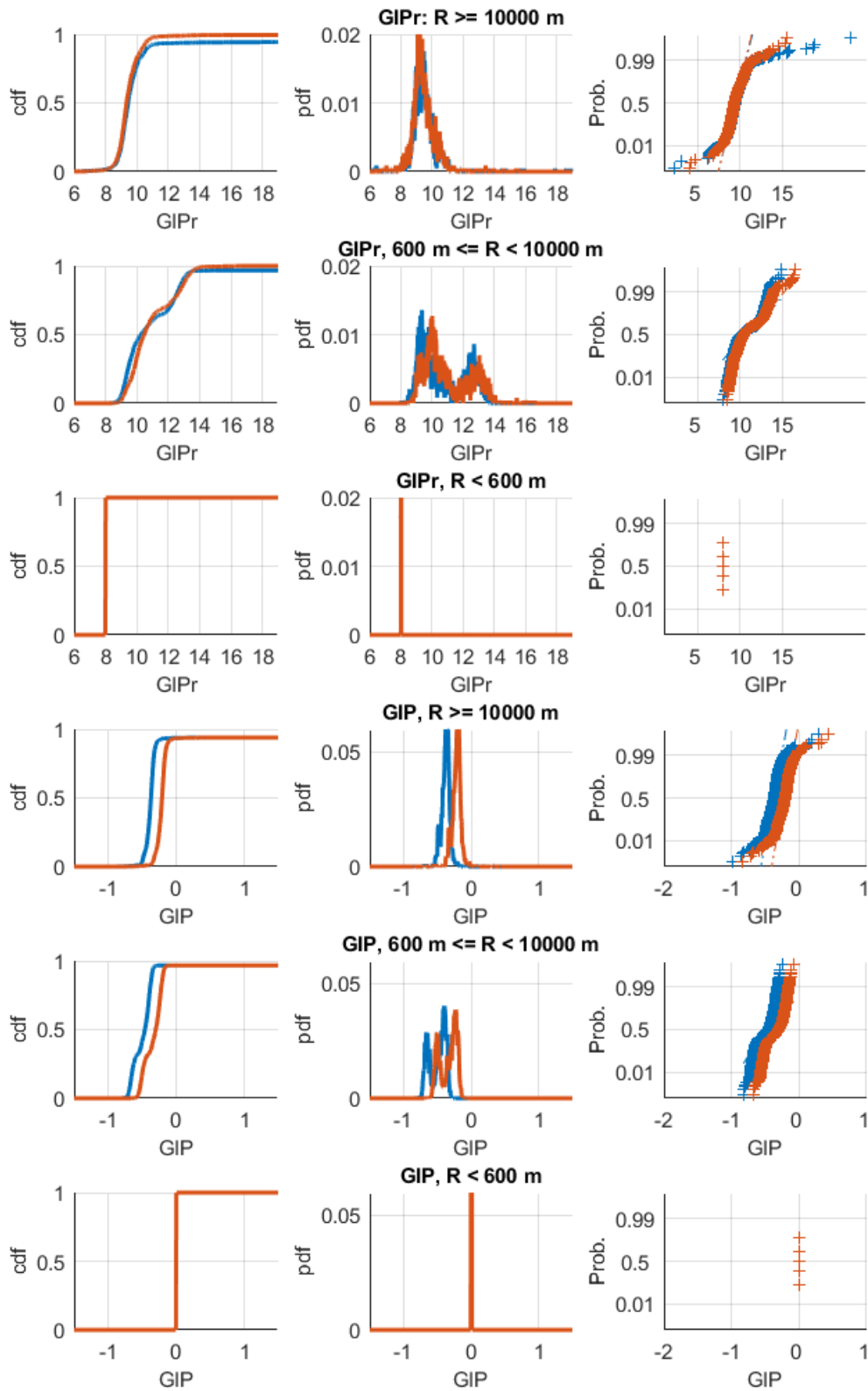


Figure 12. Results for Bdl 412N: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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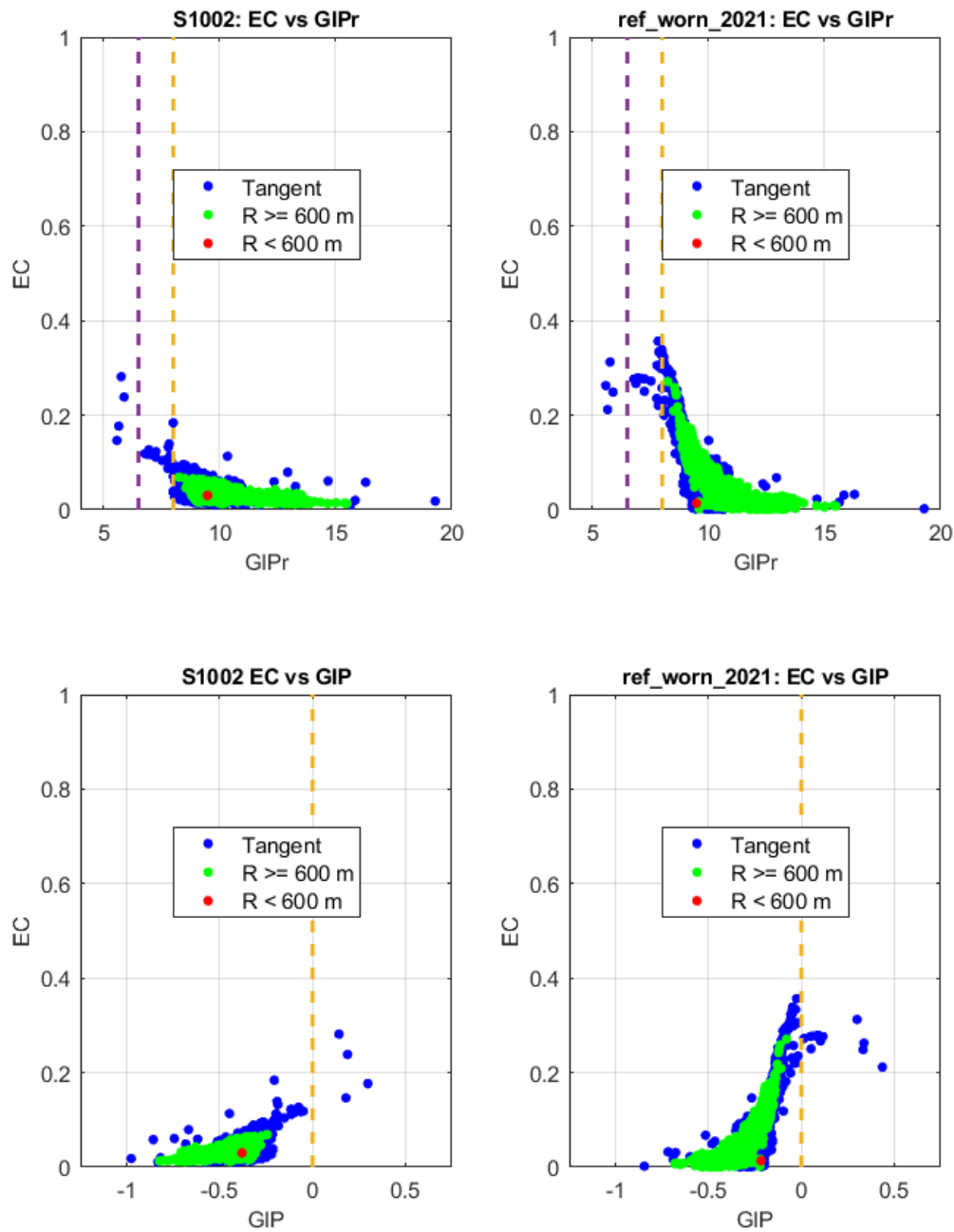


Figure 13. Results for Bdl 412N: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIP for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

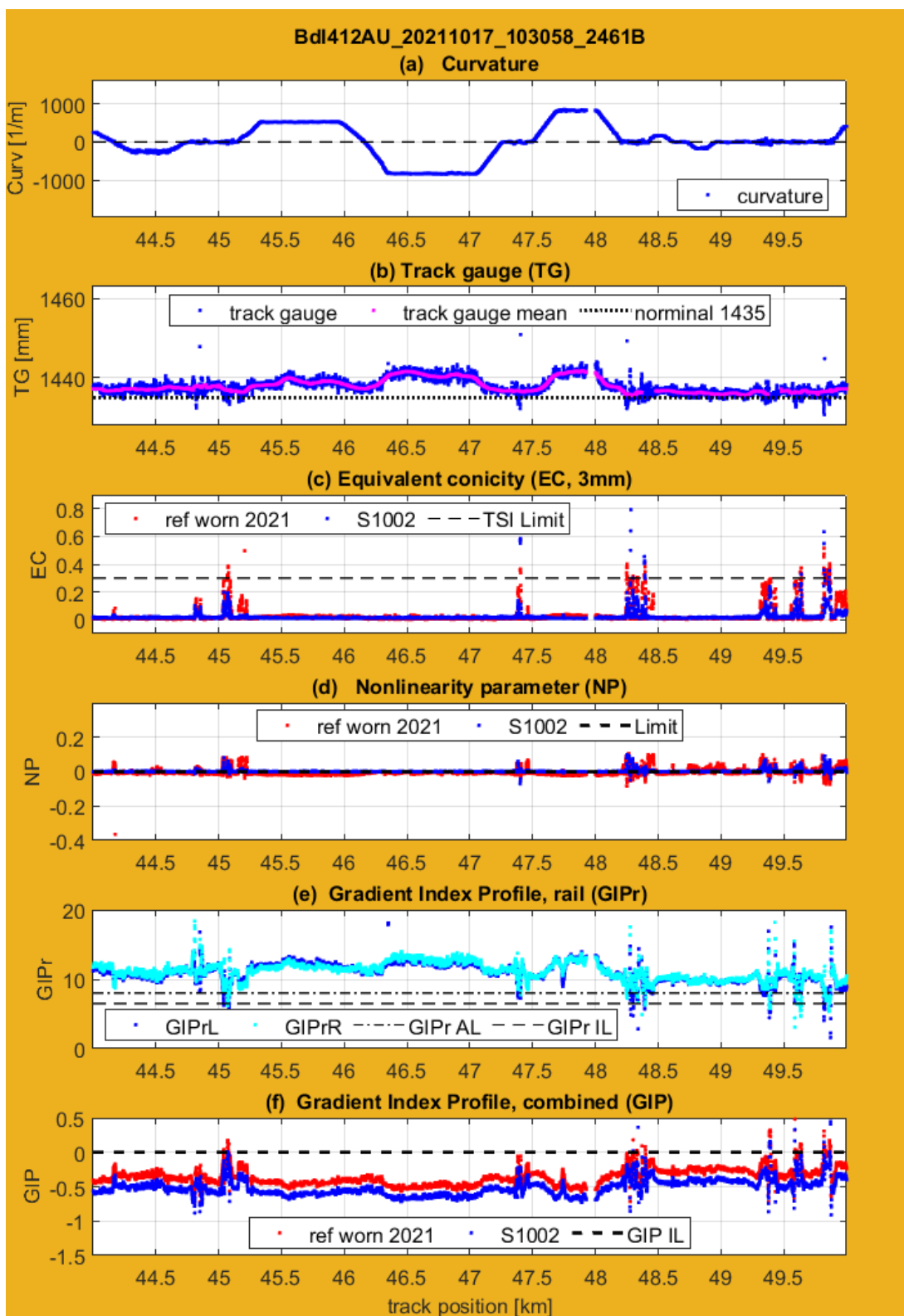


Figure 14. Results for Bdl 412U: (a). Curvature ([1/m] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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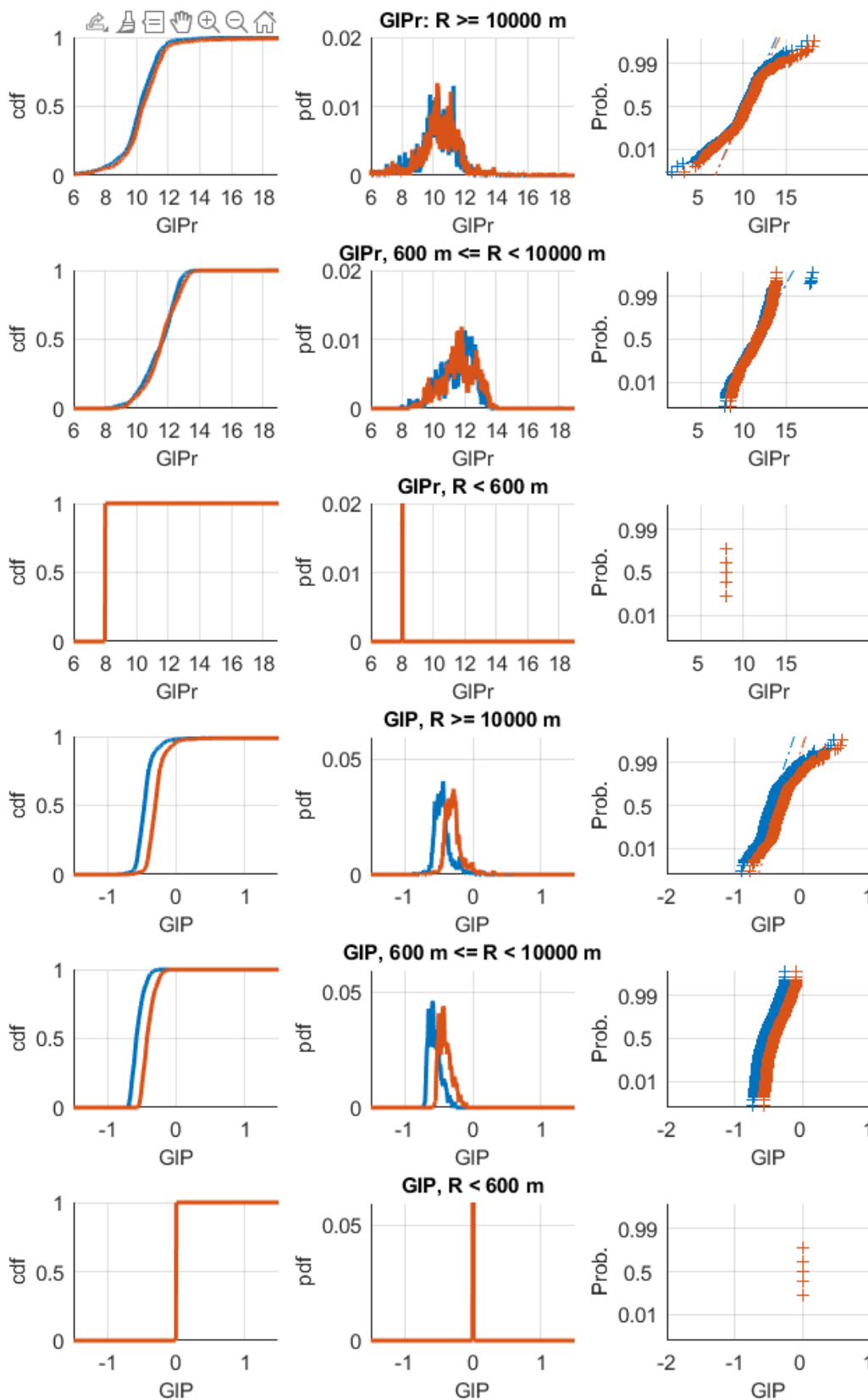


Figure 15. Results for Bdl 412U: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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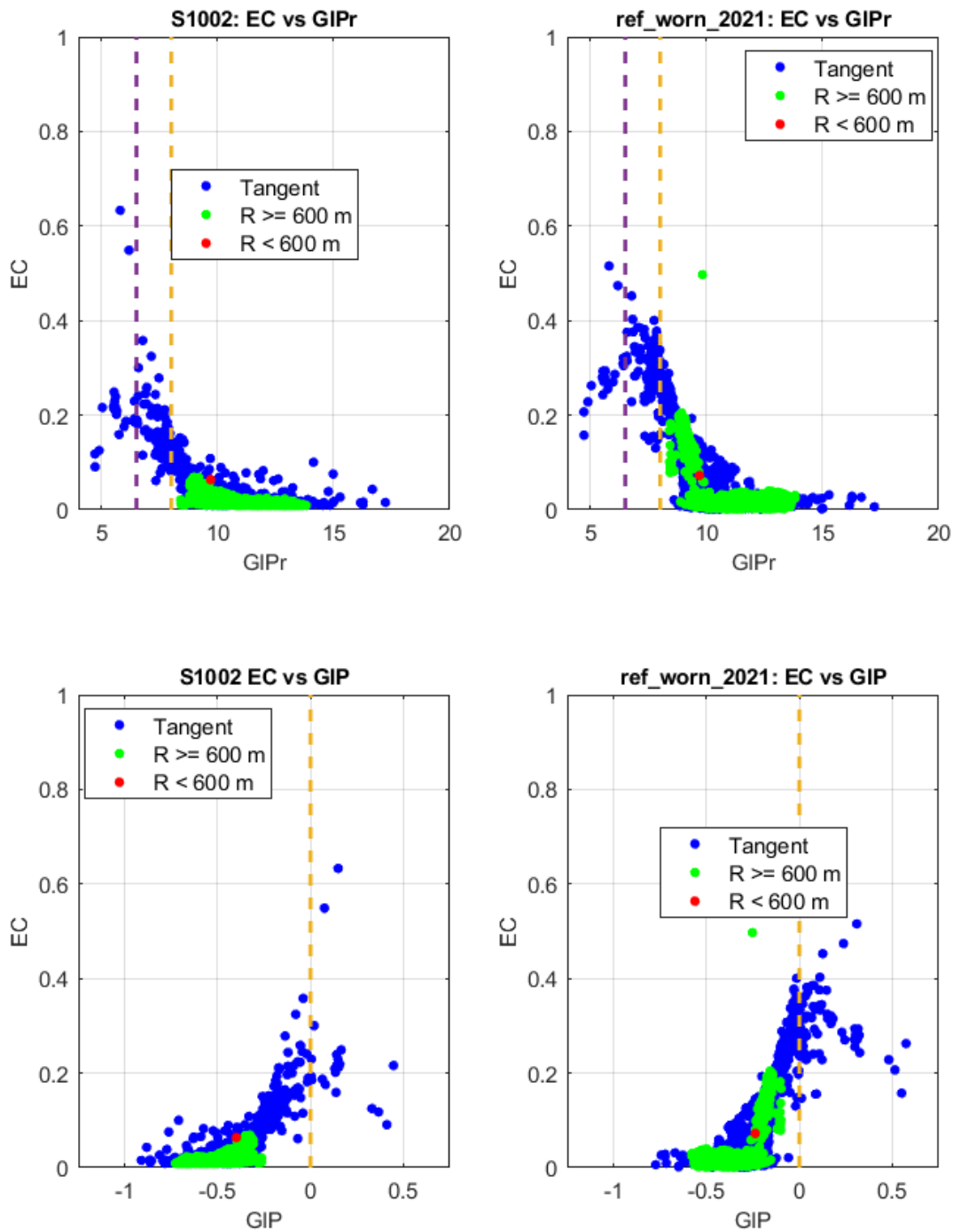


Figure 16. Results for Bdl 412U: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

### 4.3 Bdl 416: Katrineholm - Hallsberg

Bdl 416, a part of track sections (Bandel) connecting Katrineholms C and Hallsberg, as depicted in Figure 17, comprises a ballasted double track utilizing both 60E1 and 50E3 rail and concrete sleepers, and including numerous curves with radii ranging from 900 m to 10,000 m. Information from the databases of BIS and OPTRAM indicates that Bdl 416 has undergone various renewal activities dating back to the 1990s and rail surface maintenance actions have been carried out during recent years. It is worth mentioning that there have been reports of running instability on tangent track sections of this track section and narrow track gauges were identified as the main cause.



Figure 17. Bdl 416: Katrineholm - Hallsberg

Figure 18 summarizes the main results for Bdl 416N, indicating that the wheel-rail contact geometry conditions are generally very good. For the majority of the track locations, the in-service EC values with ref\_worn\_2021 remain well below the TSI limit value of 0.3. The Nonlinearity Parameters (NP) exhibit positive values, the GIPrL and GIPrR values are well above the proposed Alert Limit value (GIPrAL) of 8.0, and the corresponding GIP values are well below zero.

In Figure 19, cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP are summarized. Notably, although the differences between Zone A and Zone B can still be identified, they are much smaller than those in previous parts of track sections Bdl 410 and 412. Additionally, there are still no results available for Zone C.

Figure 20 displays scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIP. Similar trends are observed in Zone A and B, indicating strong correlations between EC and GIPr, GIP.

Similar observations and results for Bdl 416U are depicted in Figure 21, Figure 22 and Figure 23.

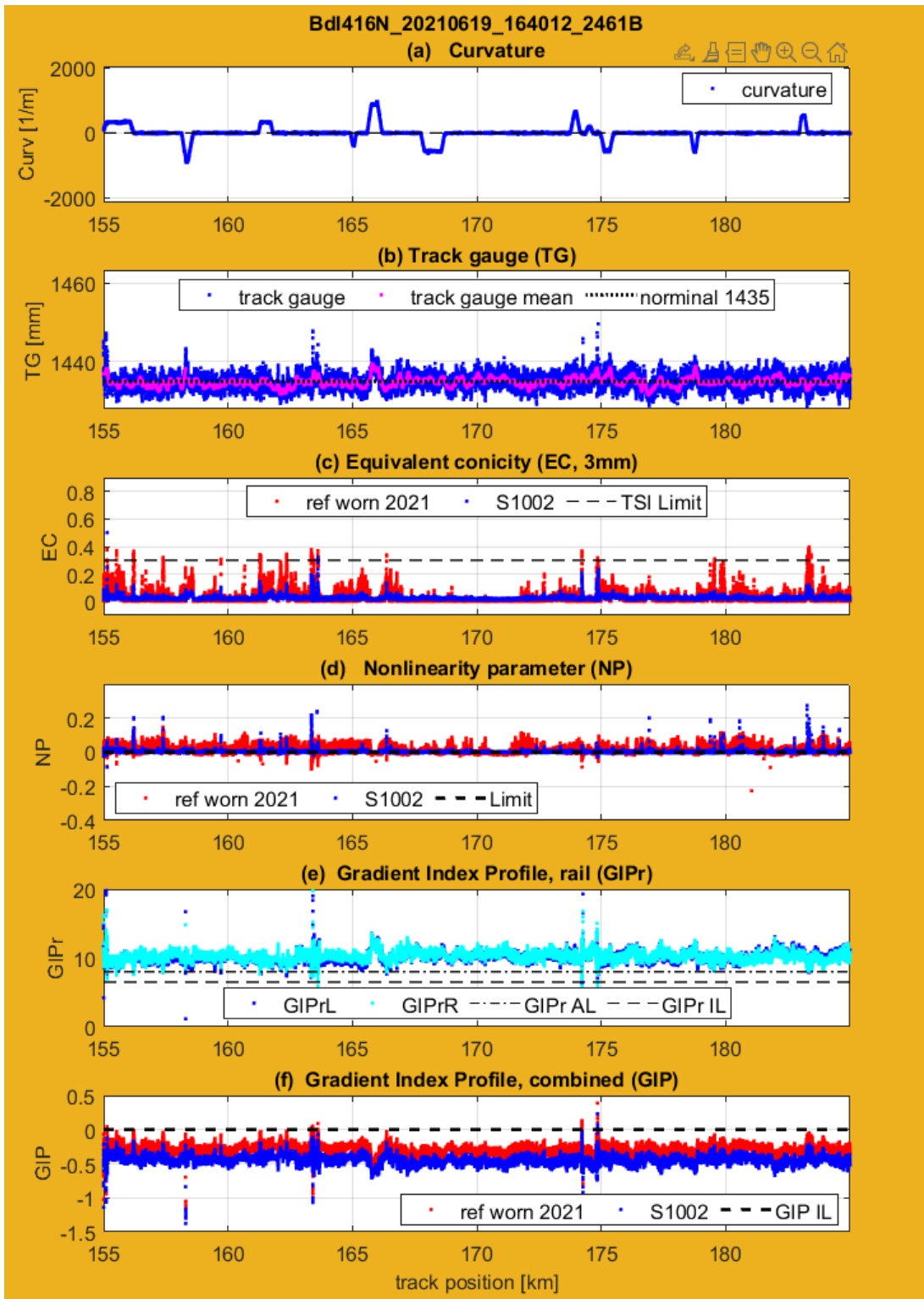


Figure 18. Results for Bdl 416N: (a). Curvature ( $1/m$  scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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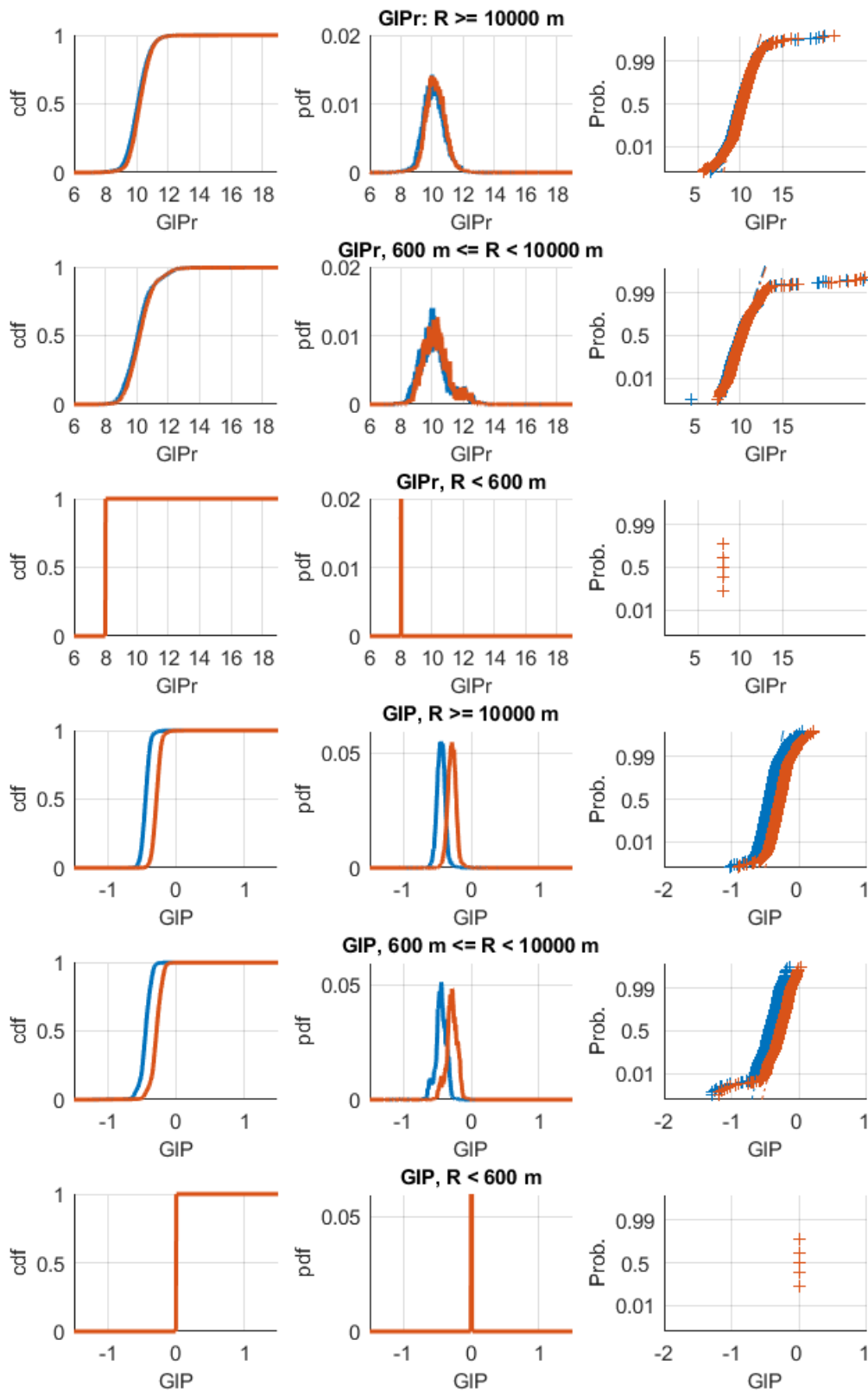


Figure 19. Results for Bdl 416N: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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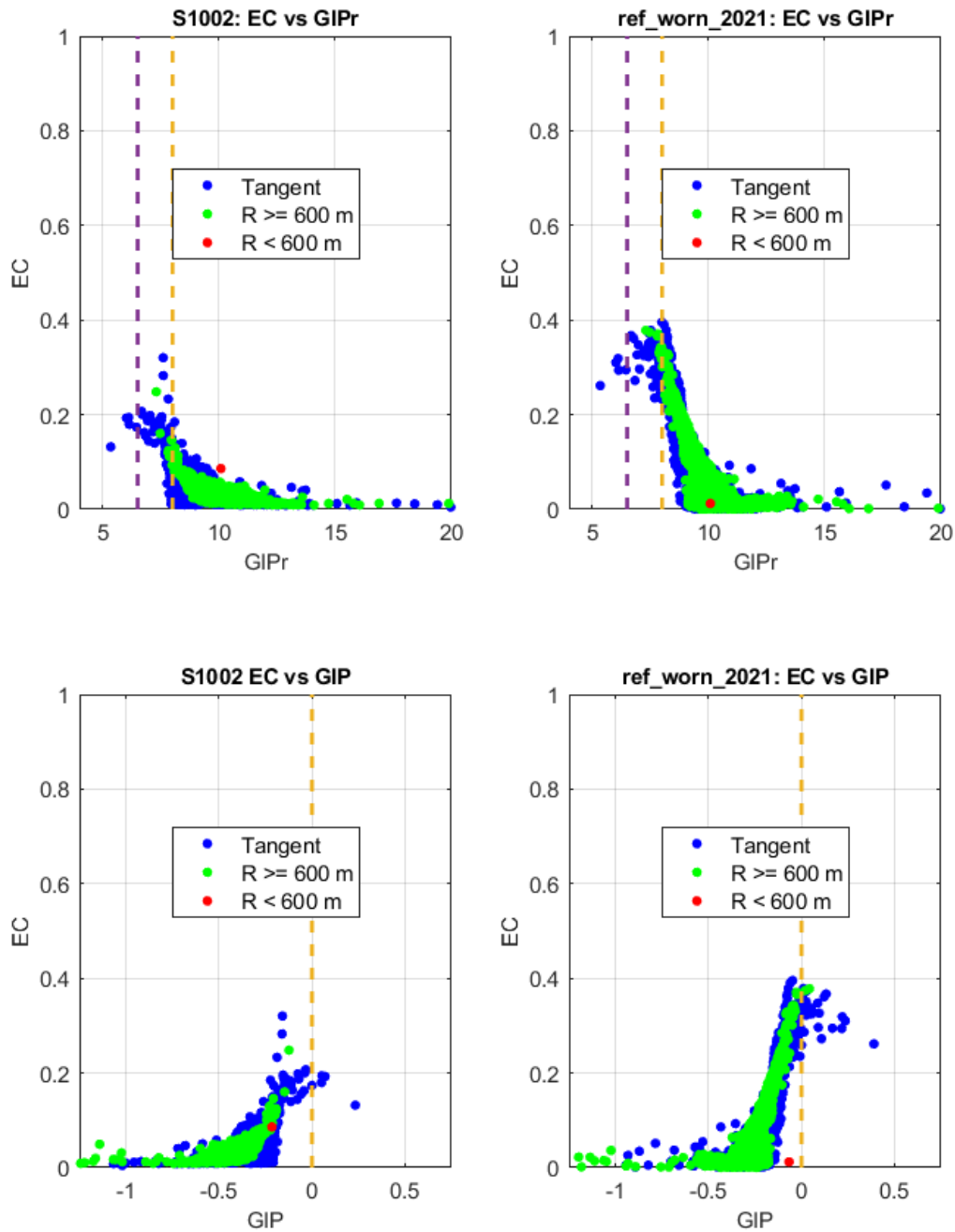


Figure 20. Results for Bdl 416N: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIP for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

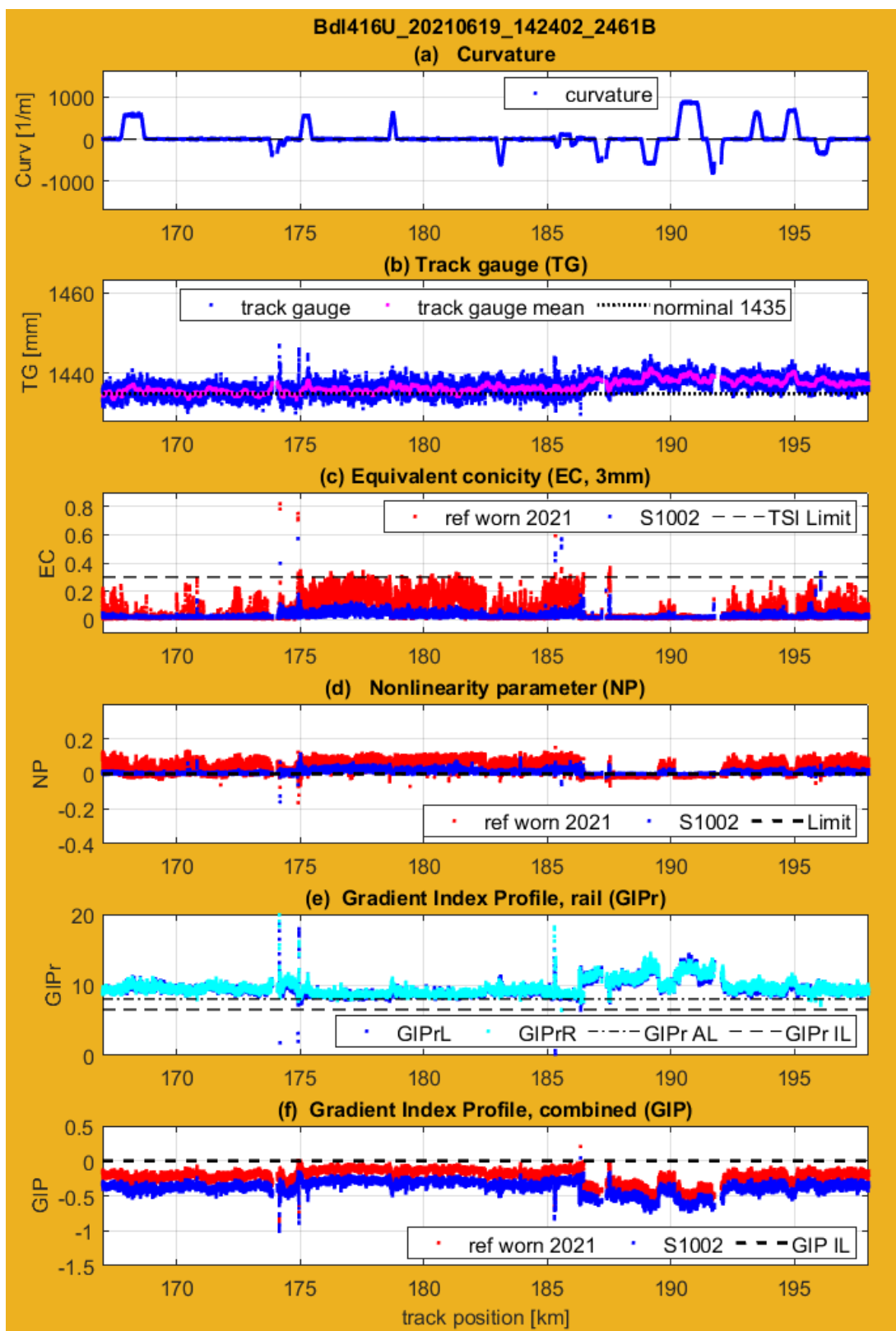


Figure 21. Results for Bdl 416U: (a). Curvature [ $1/m$ ] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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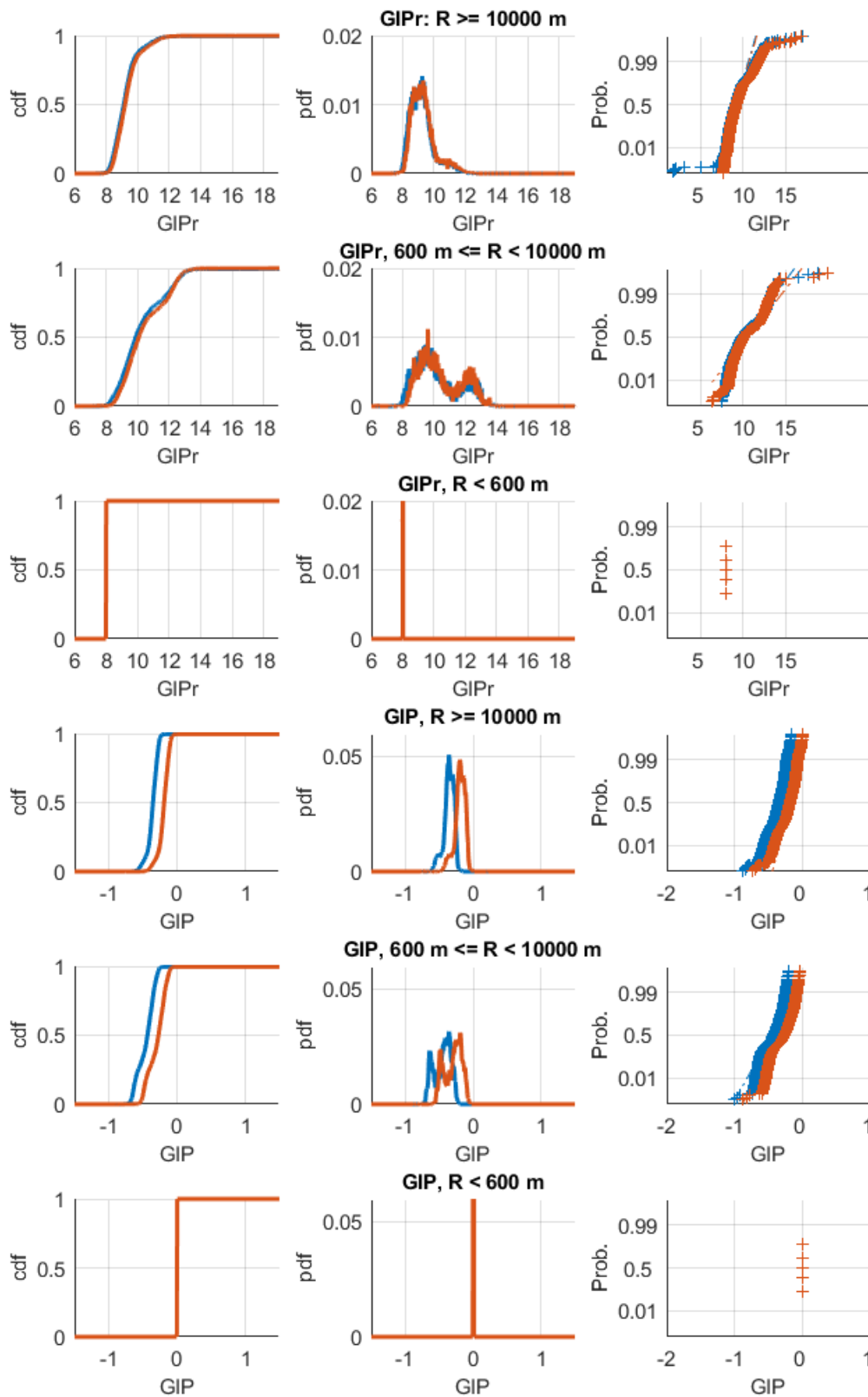


Figure 22. Results for Bdl 416U: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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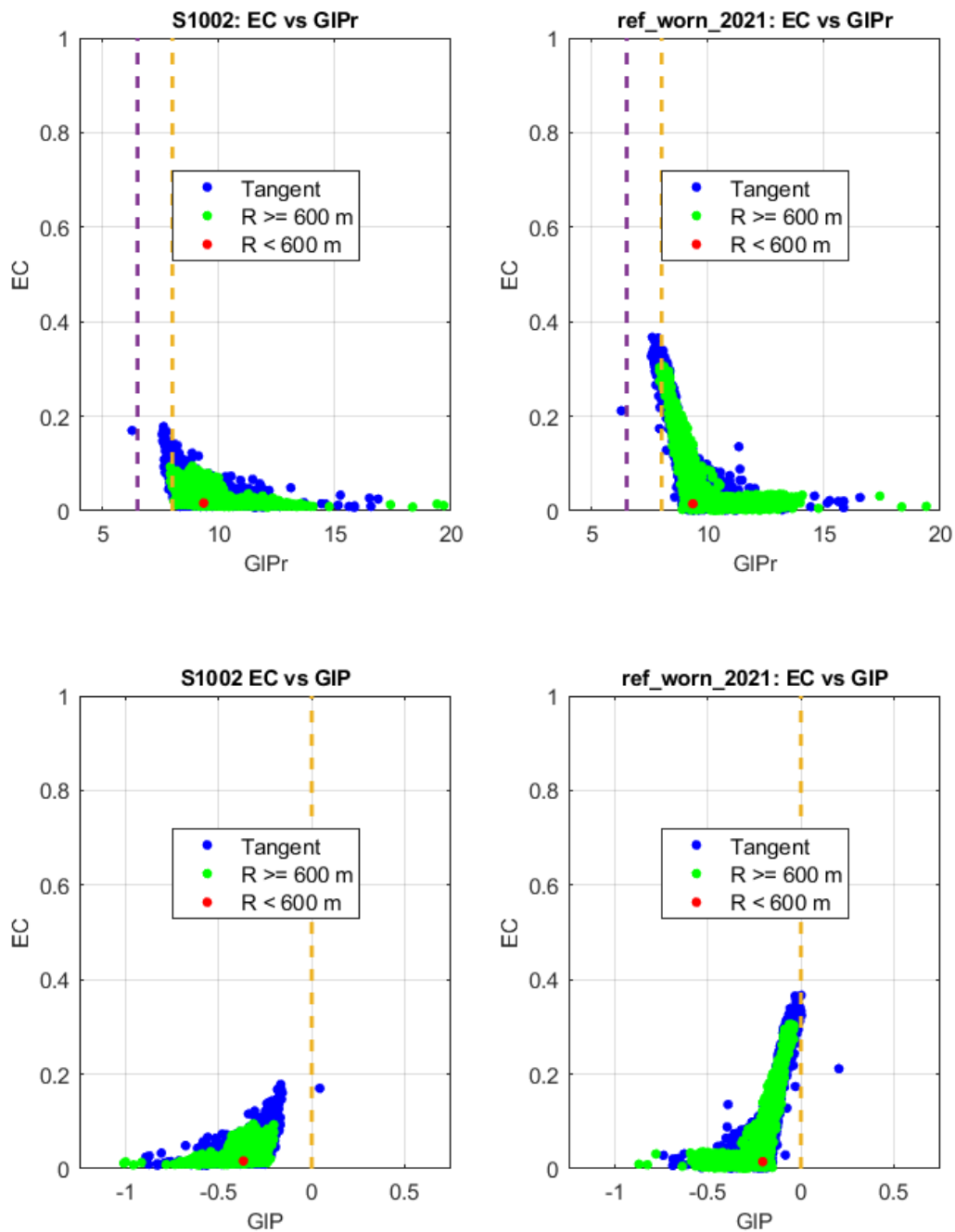


Figure 23. Results for Bdl 416U: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

#### 4.4 Bdl 511: Östansjö (Öj) – Laxå (Lå)

Bdl 511, a part of track sections (Bandel) located between Östansjö (Öj) and Laxå (Lå), as depicted in Figure 24, comprises a ballasted double track predominantly utilizing 60E1 rail and concrete sleepers with a spacing of 65 cm, featuring only a few large curves ranging from 1,321 m to 7,000 m. Information from the databases of BIS and OPTRAM indicates that Bdl 511 has undergone various renewal activities dating back to the 1990s and rail surface maintenance actions (grinding) in recent years.

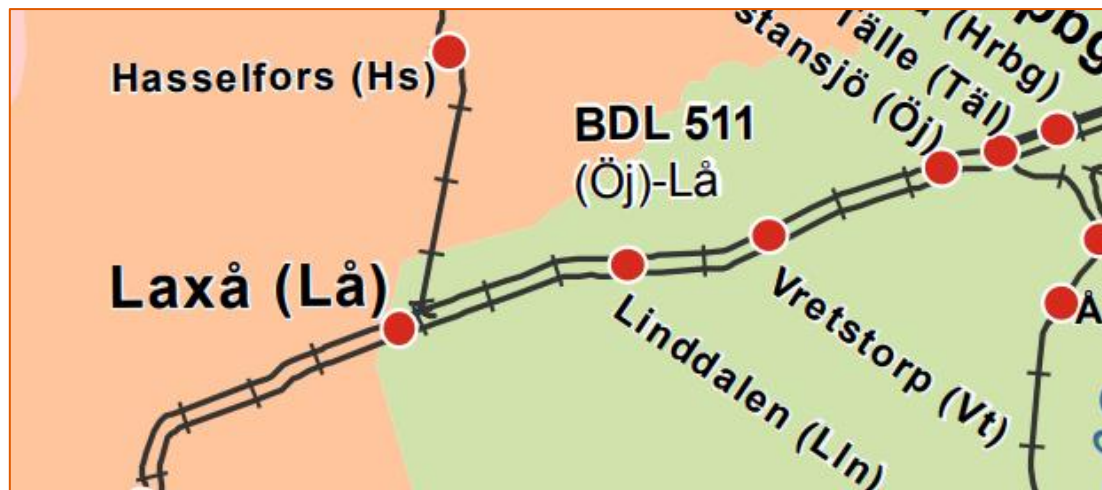


Figure 24. Bdl 511: Östansjö (Öj) and Laxå (Lå).

Figure 25 summarizes the results for Bdl 511A N, including curvatures, track gauges (TG), equivalent conicities (EC S1102 and EC ref\_worn\_2021), Nonlinearity Parameters (NP), Gradient Index Profiles for Rail (GIPrL and GIPrR) and Gradient Index Profiles for combined wheel-rail (GIP S1002 and GIP ref\_worn\_2021). A few specific locations show EC ref\_worn\_2021 values exceeding 0.3 and GIPr values below GIPrAL. For majority of the track locations, both track EC values with S1002 and in-service EC values with ref\_worn\_2021 are very low, likely due to wider track gauges, indicating potential issues related to low frequency carbody motion.

In Figure 26, a summary of cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP is presented. Notably, although the differences between Zone A and Zone B can still be identified, they are much smaller than those in previous parts of track sections Bdl 410, 412 and 416. Additionally, there are still no results available for Zone C.

Figure 27 displays scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr. Similar trends are observed in Zone A and B, indicating strong correlations between EC and GIPr/GIP.

Similar observations and results for Bdl 511A U are depicted in Figure 28, Figure 29 and Figure 30. In particular, a difference between GIPrL and GIPrR is observed, suggesting that left and right rails at this Bandel have different worn conditions.

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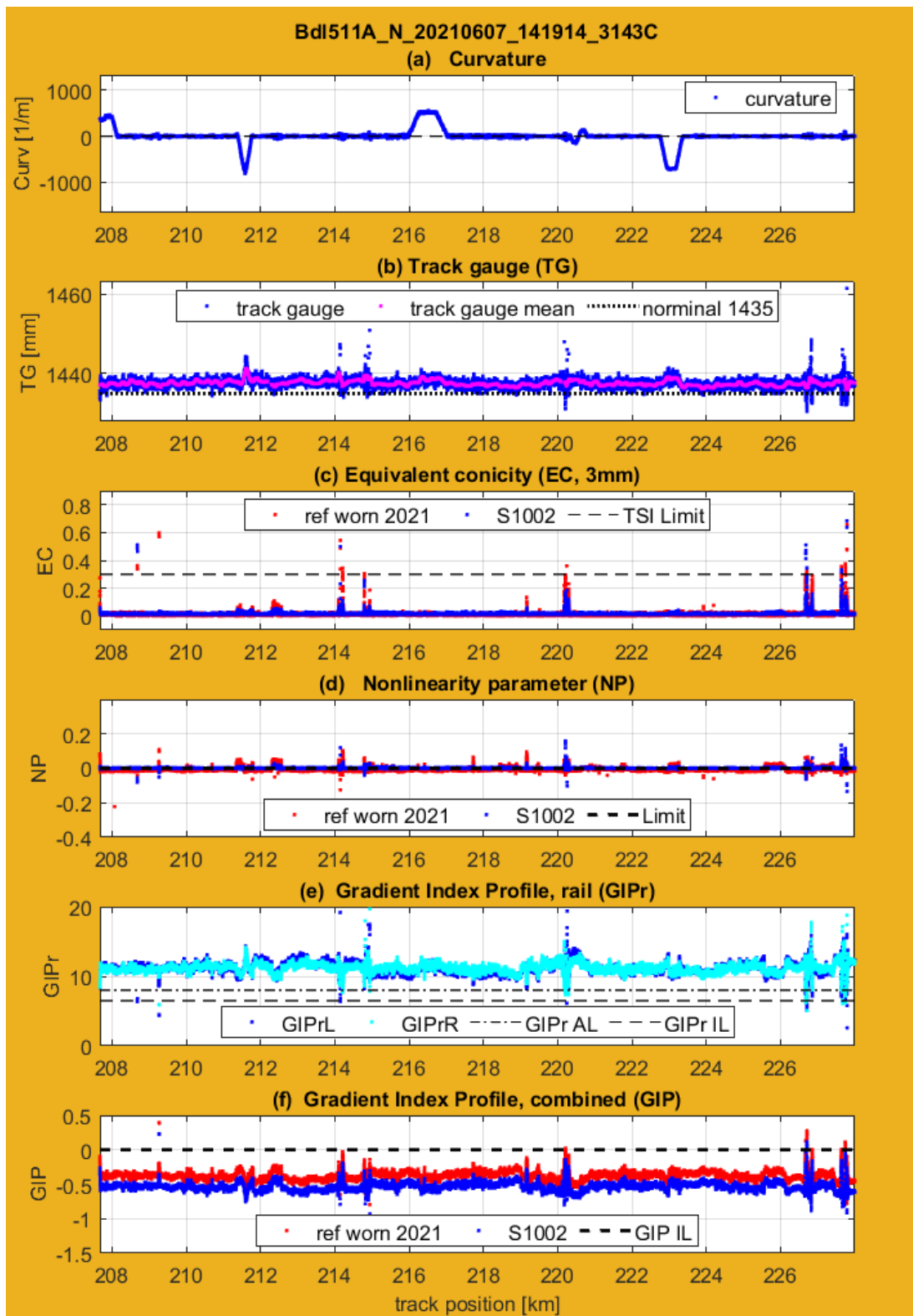


Figure 25. Results for Bdl 511A N: (a). Curvature ([1/m] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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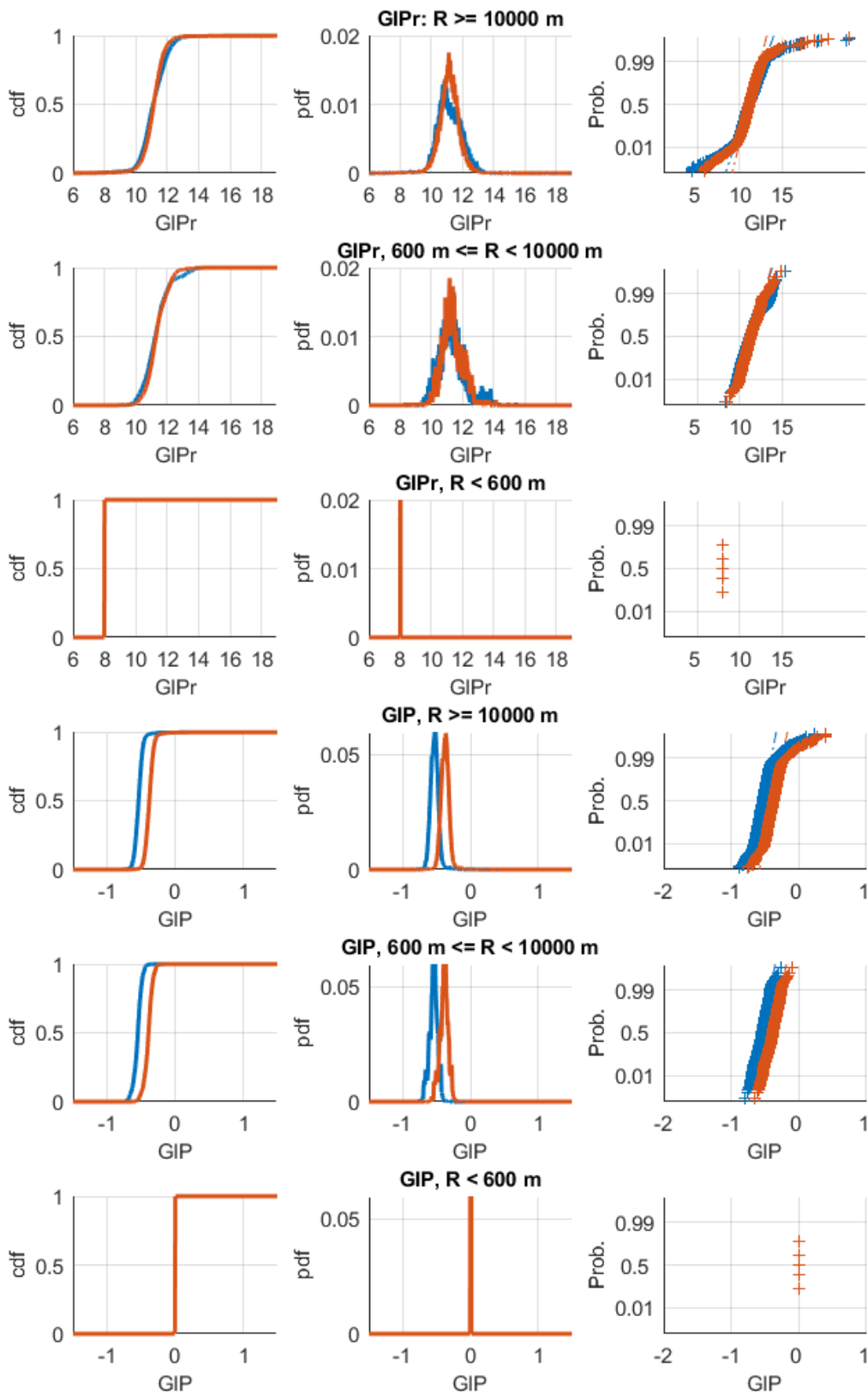


Figure 26. Results for Bdl 511A N: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R < 10,000$  m and C) small curves with  $R \leq 600$  m.

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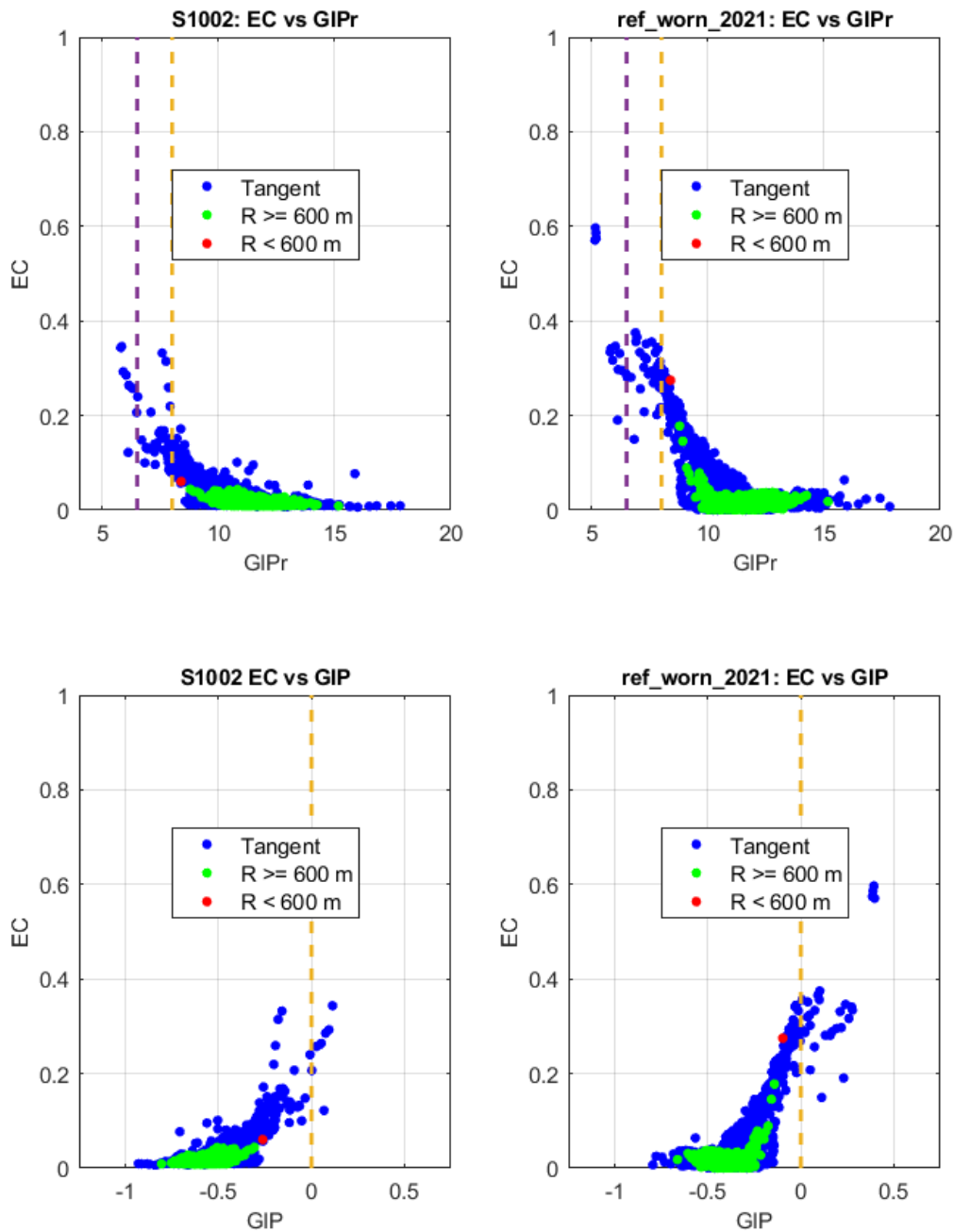


Figure 27. Results for Bdl 511A N: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

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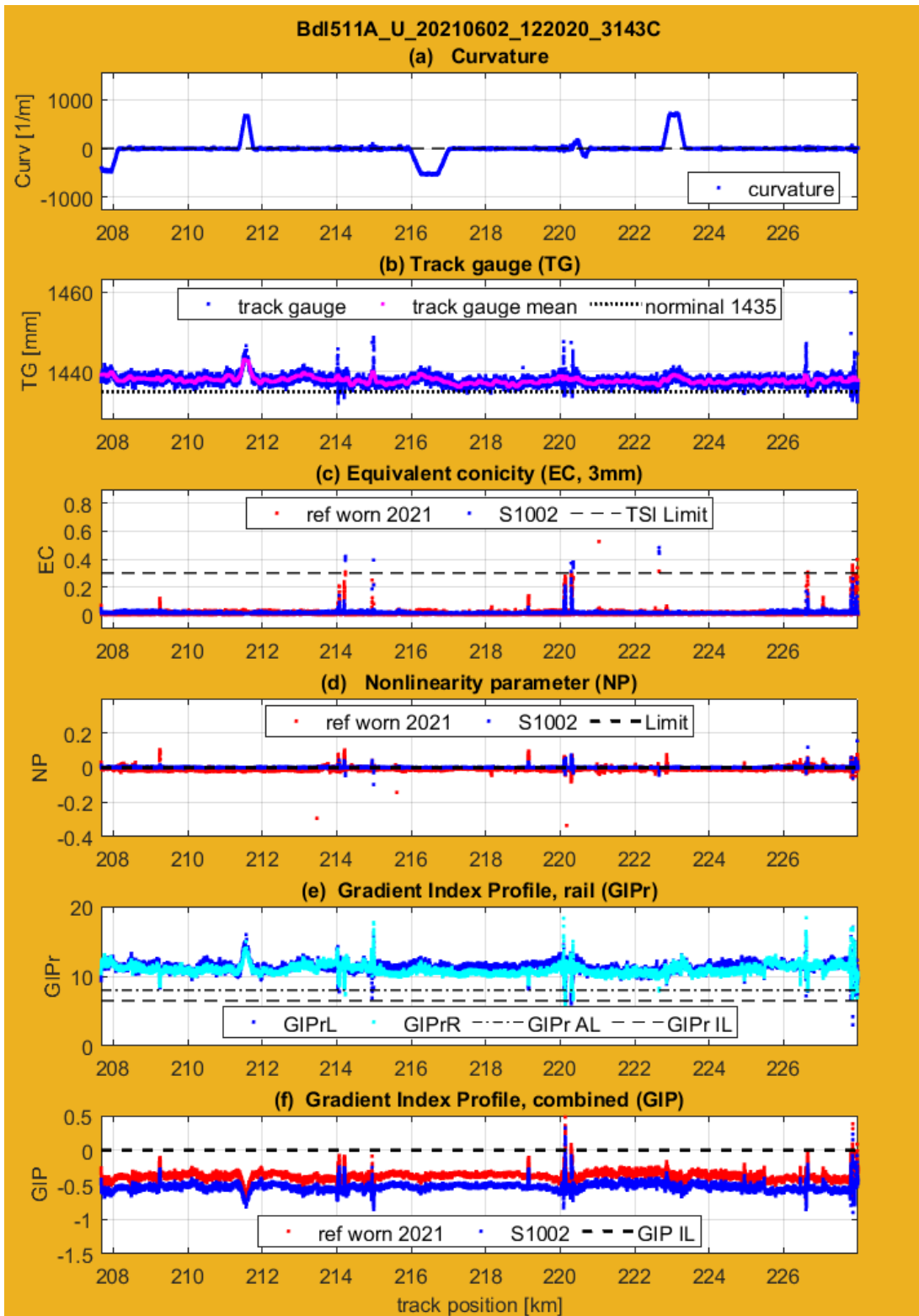


Figure 28. Results for Bdl 511A U: (a). Curvature ([1/m] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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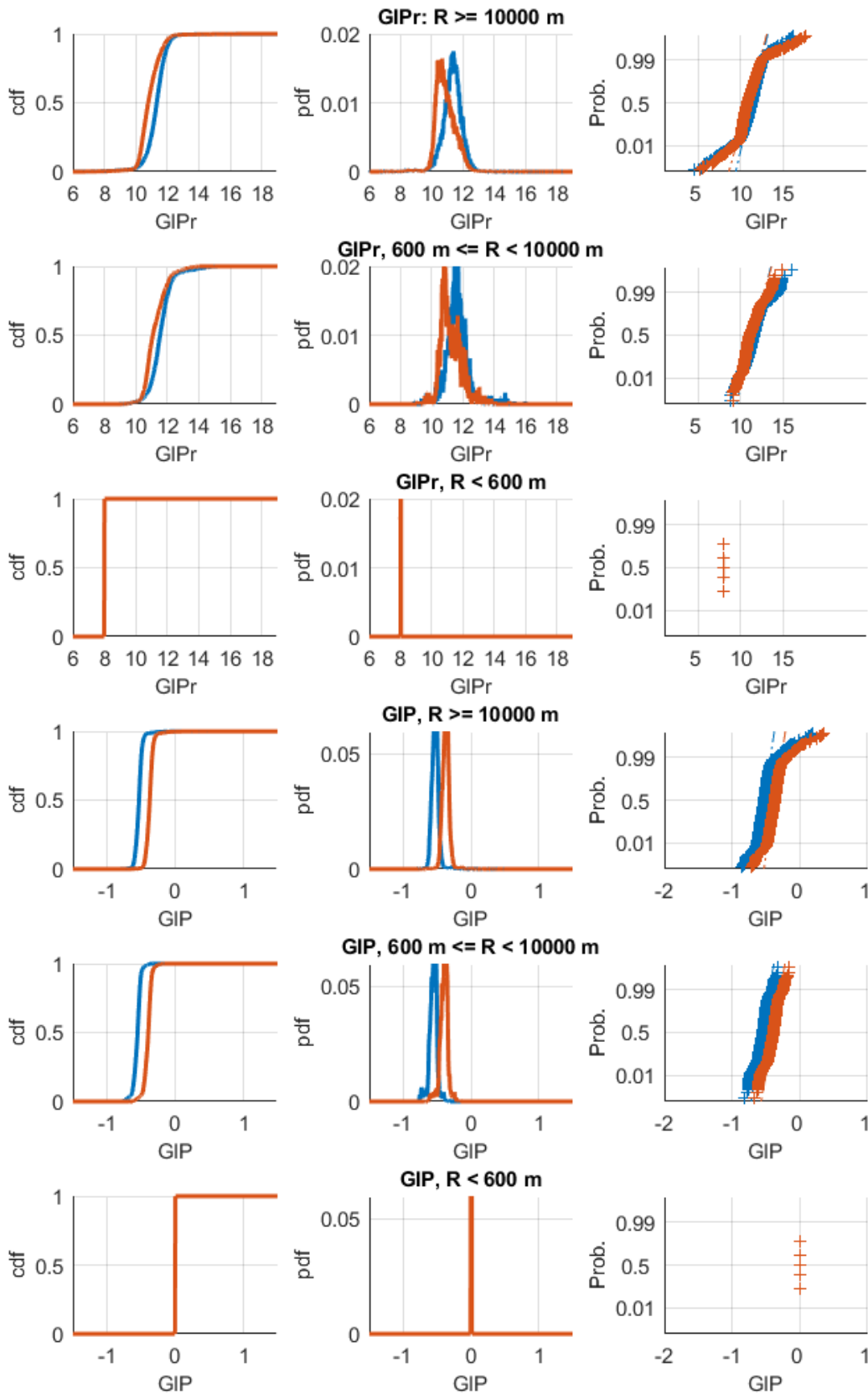


Figure 29. Results for Bdl 511A U: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R < 10,000$  m and C) small curves with  $R \leq 600$  m.

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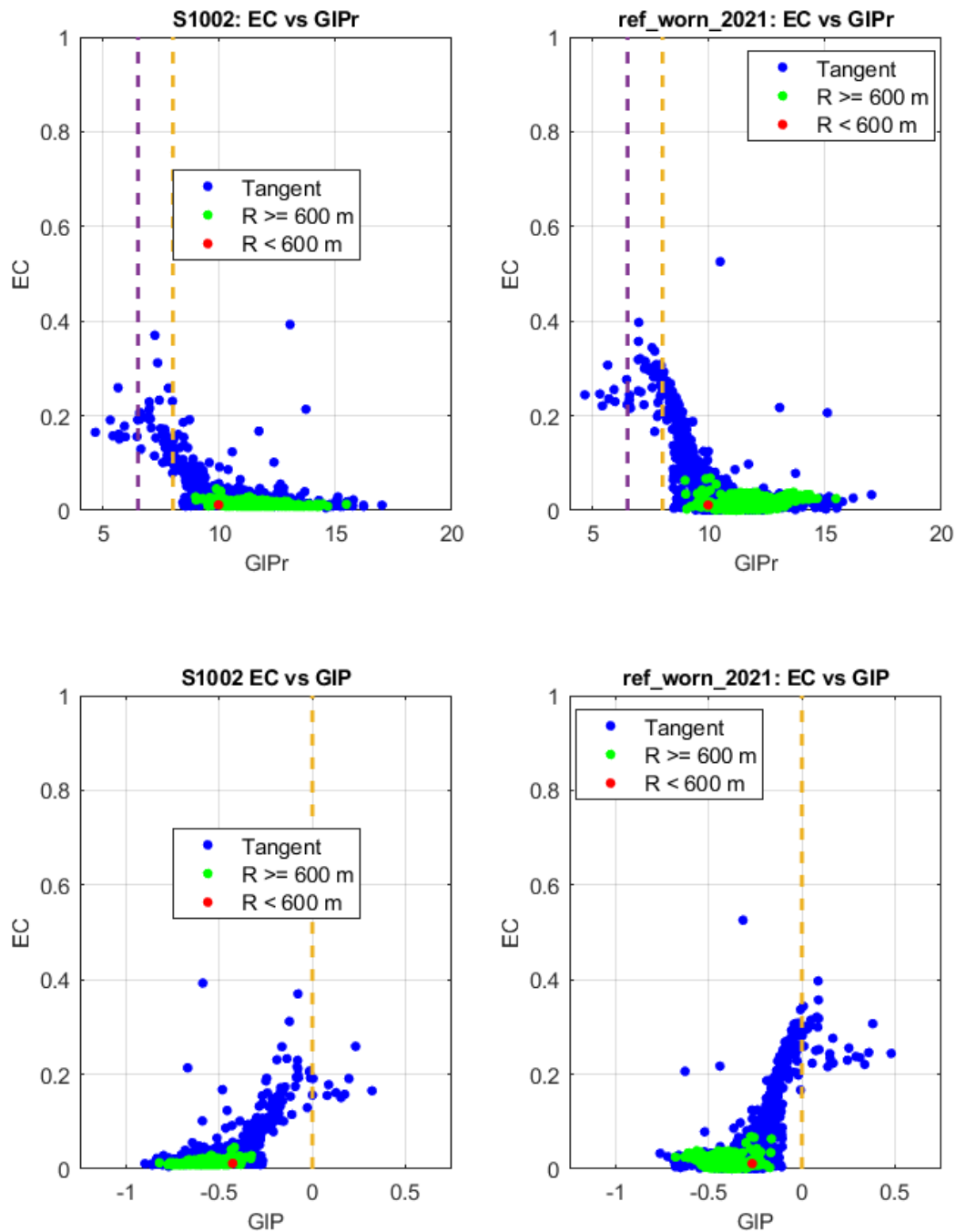


Figure 30. Results for Bdl 511A U: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

## 4.5 Bdl 512: Laxå - Falköping

Bdl 512, between Laxå (Lå) and Falköping (F) as depicted in Figure 31, consists of a ballasted double track primary employing 60E1 rail and concrete sleepers and includes numerous large and very large curves with radii ranging from 968 m up to 99,000 m. Bdl 512 has undergone various renewal activities dating back to the 1990s and rail surface maintenance actions (grinding) in recent years.

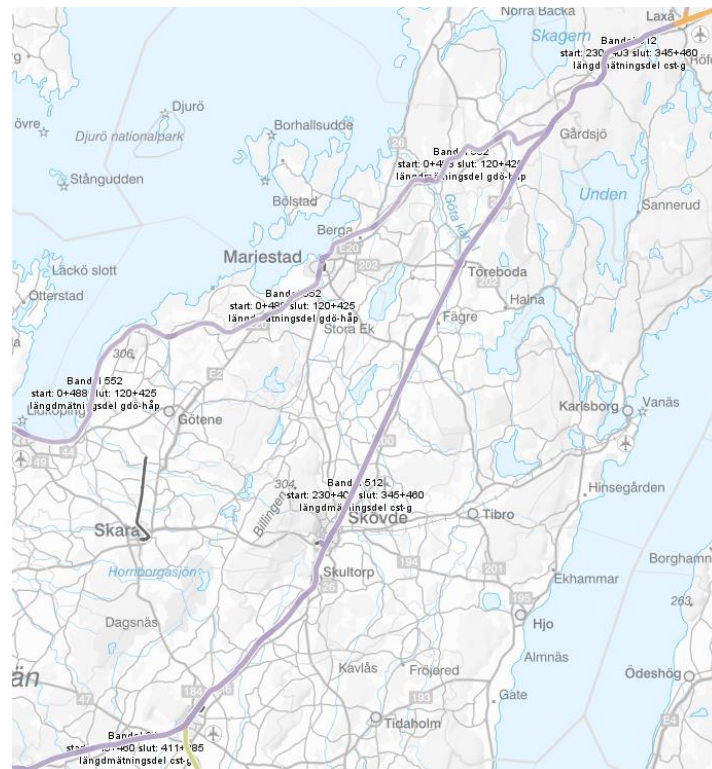


Figure 31. Bdl 512, Laxå (Lå) - Falköping (F),

Figure 32 summarizes the results for Bdl 512A N, including curvatures, track gauges (TG), equivalent conicities (EC S1102 and EC ref\_worn\_2021), Nonlinearity Parameters (NP), Gradient Index Profiles for Rail (GIPrL and GIPrR) and Gradient Index Profiles for combined wheel-rail (GIP S1002 and GIP ref\_worn\_2021).

In Figure 33, a summary of cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP is presented. Again, we observe a difference between GIPrL and GIPrR, indicating that left and right rails at Bdl512N have different worn conditions.

Figure 34 displays scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr. We observe that there exist a few specific locations where EC ref\_worn\_2021 values exceed TSI limit value of 0.3 and GIPr values fall below the proposed Intervention Limit of 6.5.

Similar results for Bdl 512U are depicted in Figure 35, Figure 36 and Figure 37. Notably, unlike Bdl512N, no extremely high values of EC ref\_worn\_2021 and low values of GIPr are present.

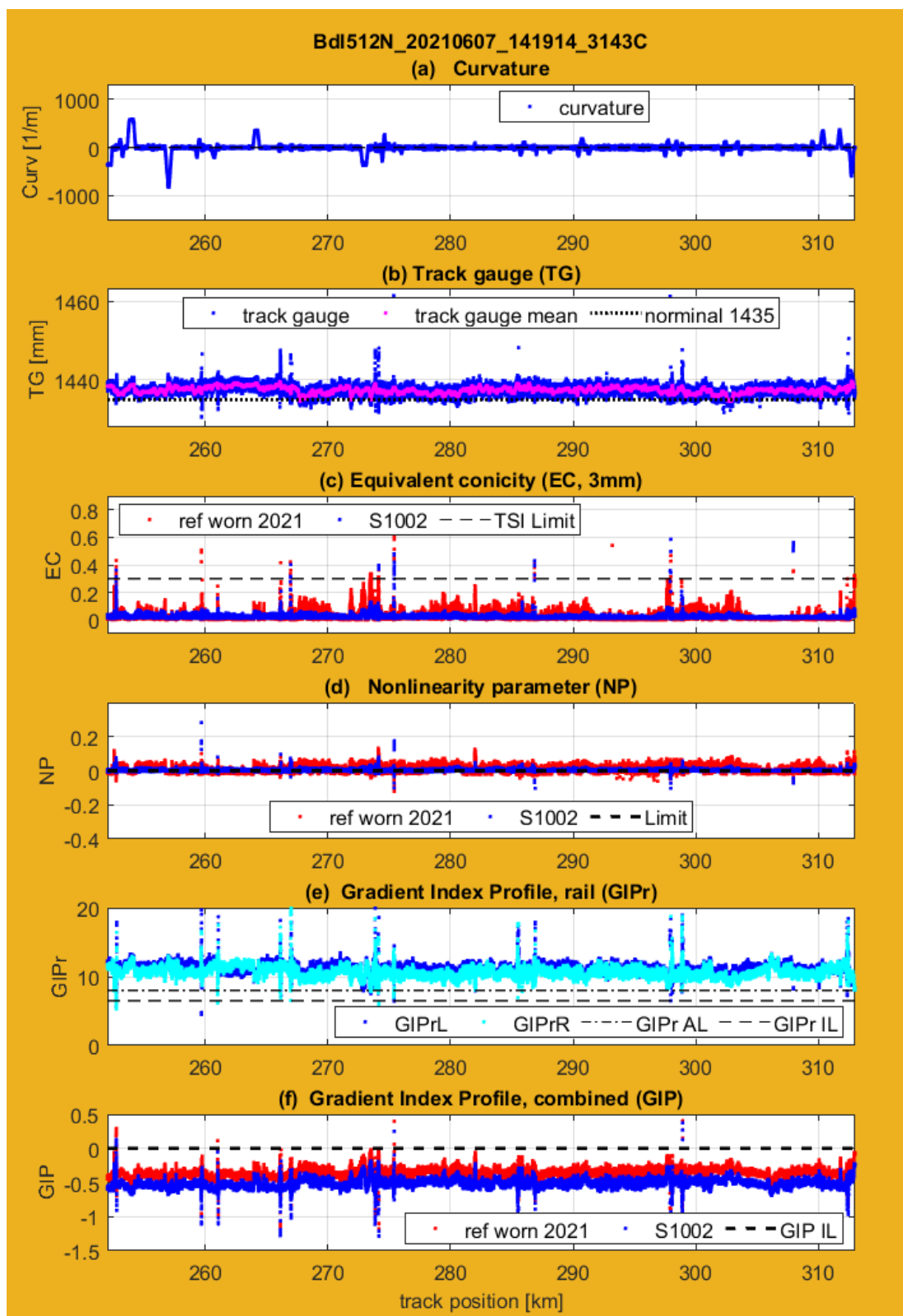


Figure 32. Results for Bdl 512N: (a). Curvature [ $1/m$ ] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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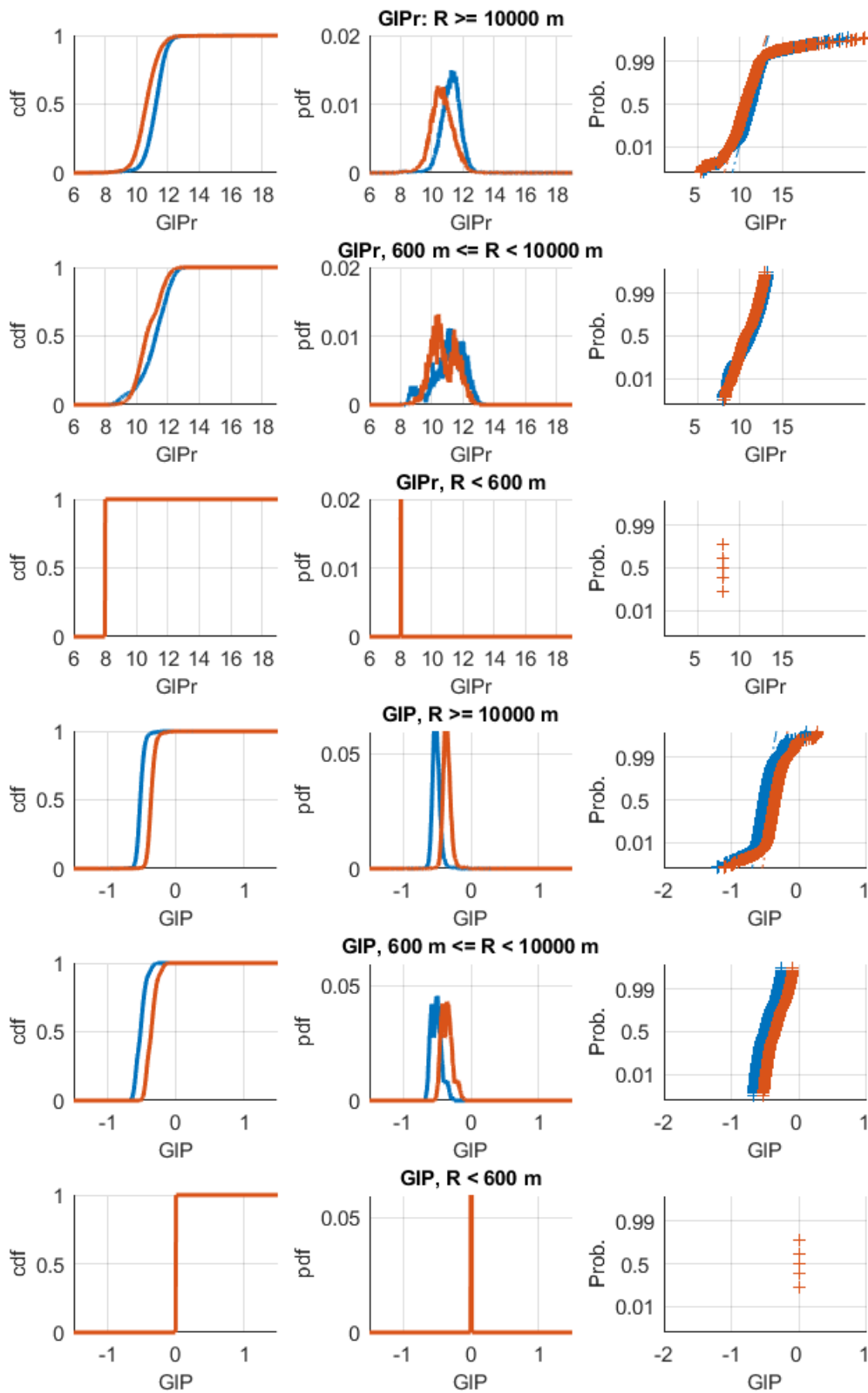


Figure 33. Results for Bdl 512N: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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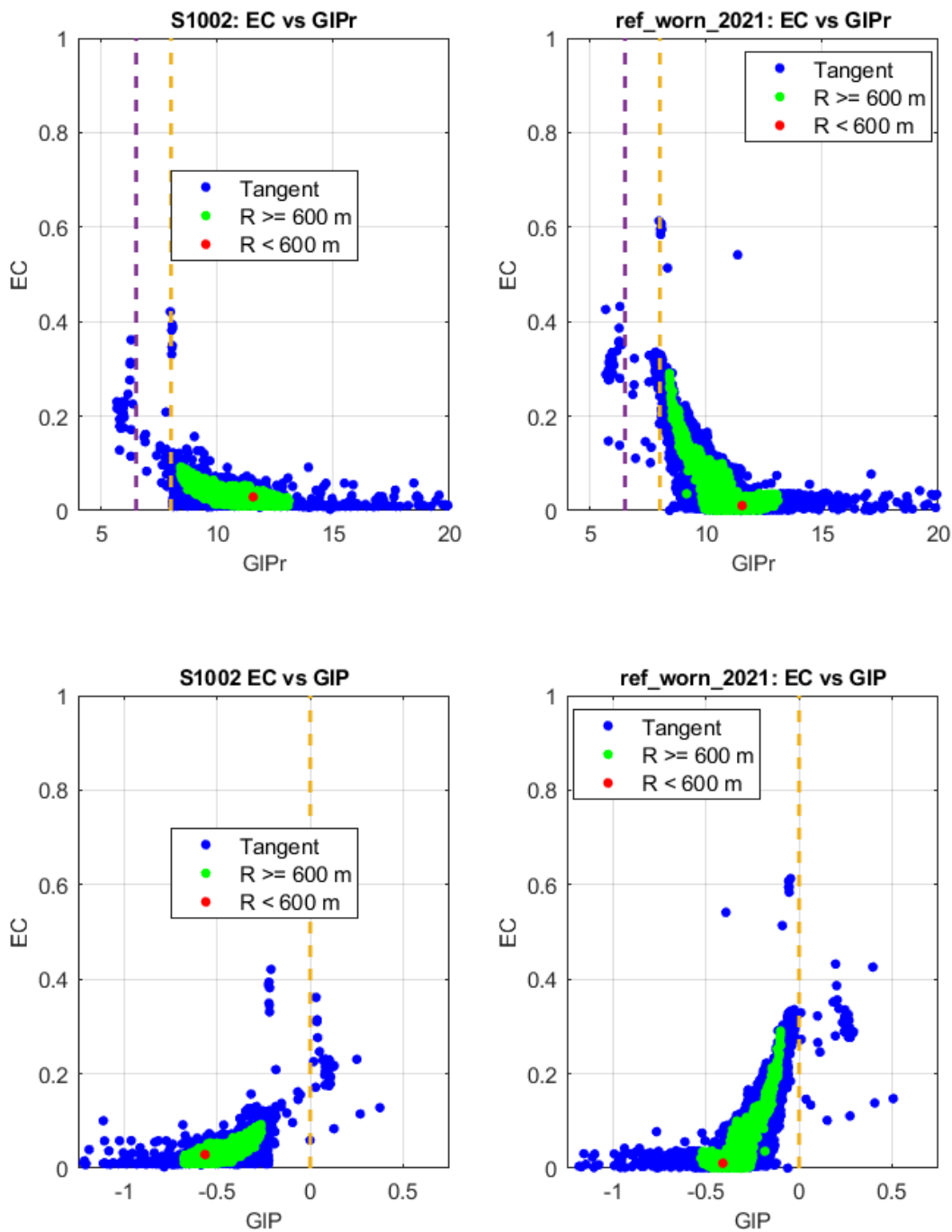


Figure 34. Results for Bdl 512N: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

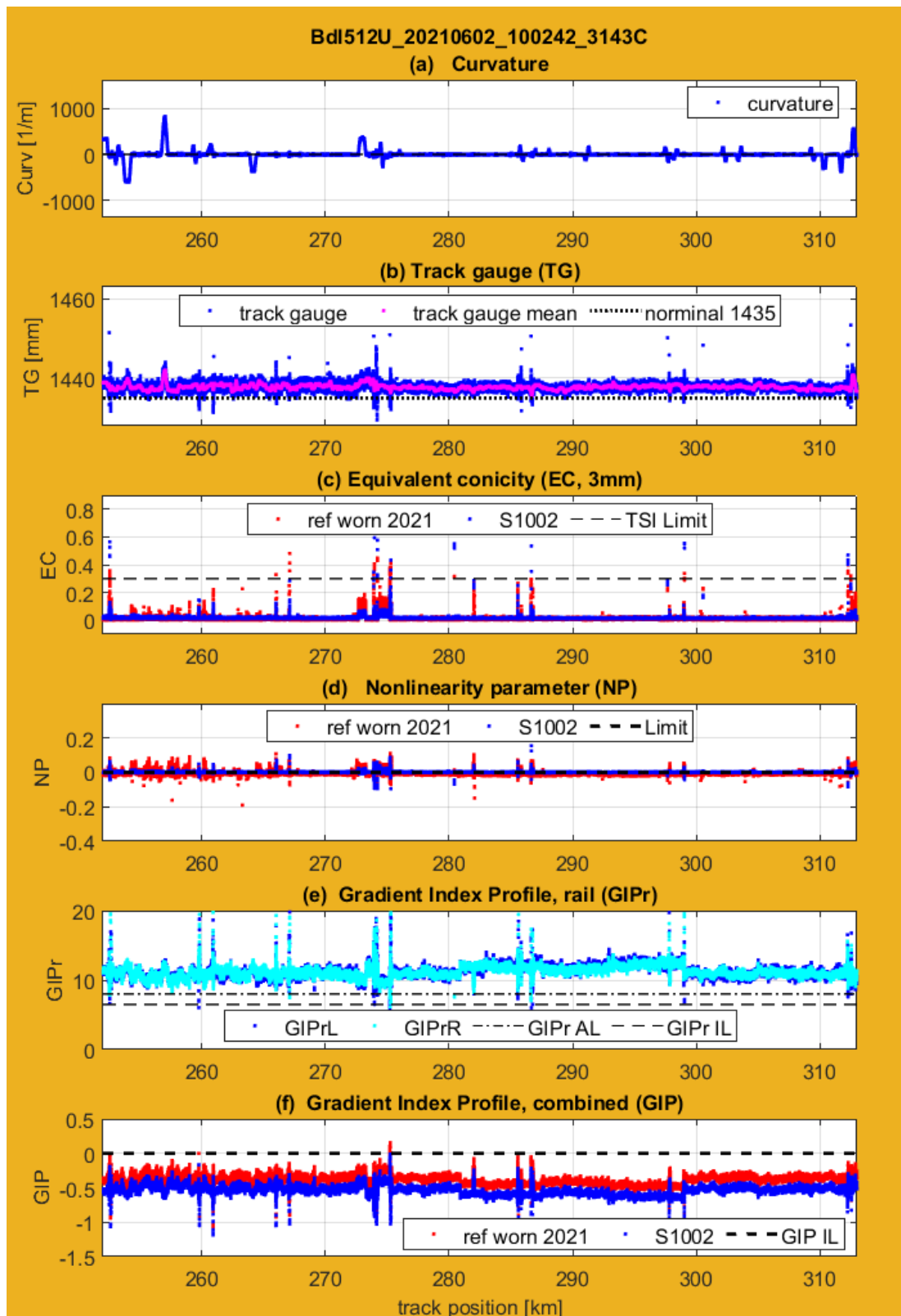


Figure 35. Results for Bdl 512U: (a). Curvature ([1/m] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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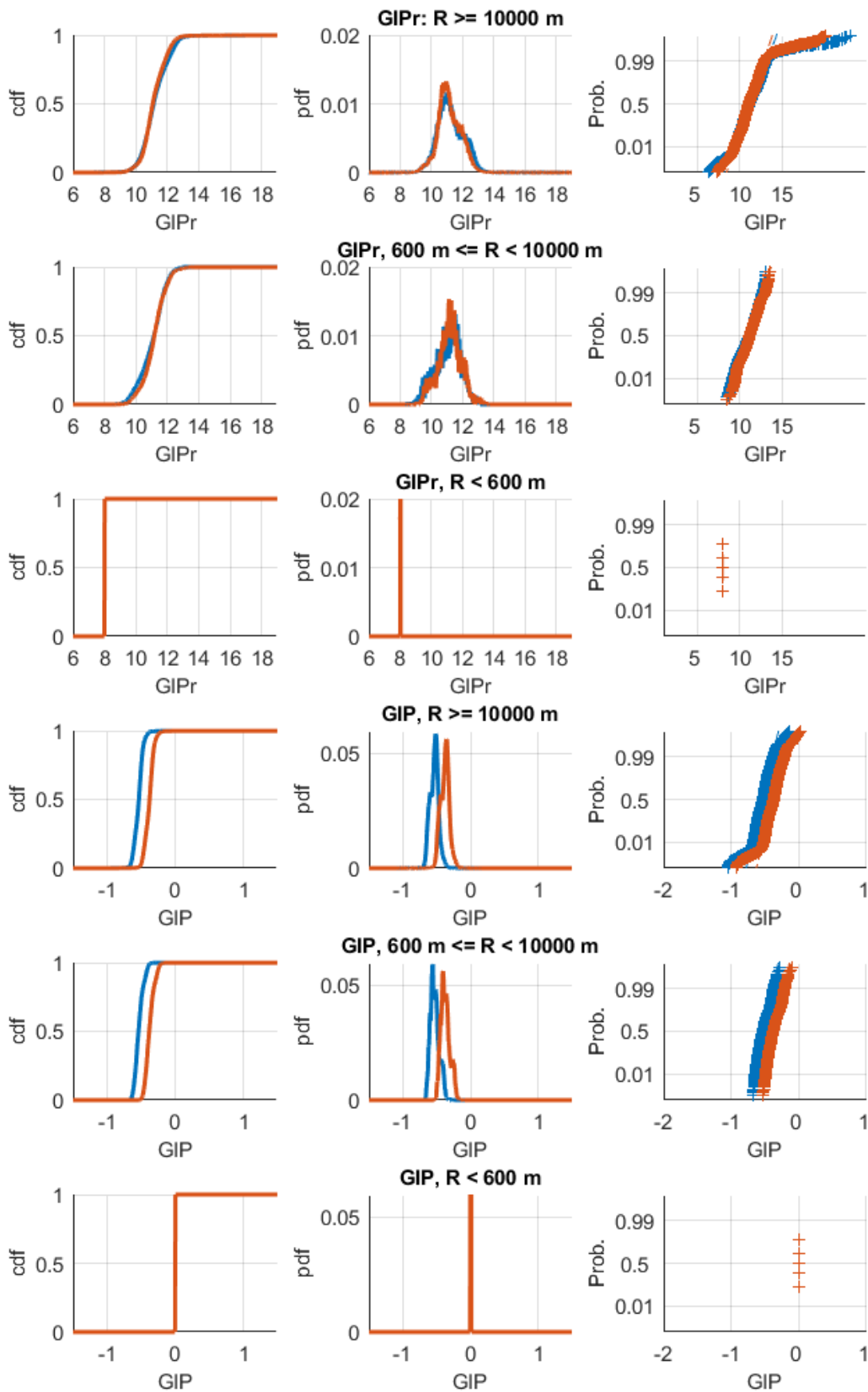


Figure 36. Results for Bdl 512U: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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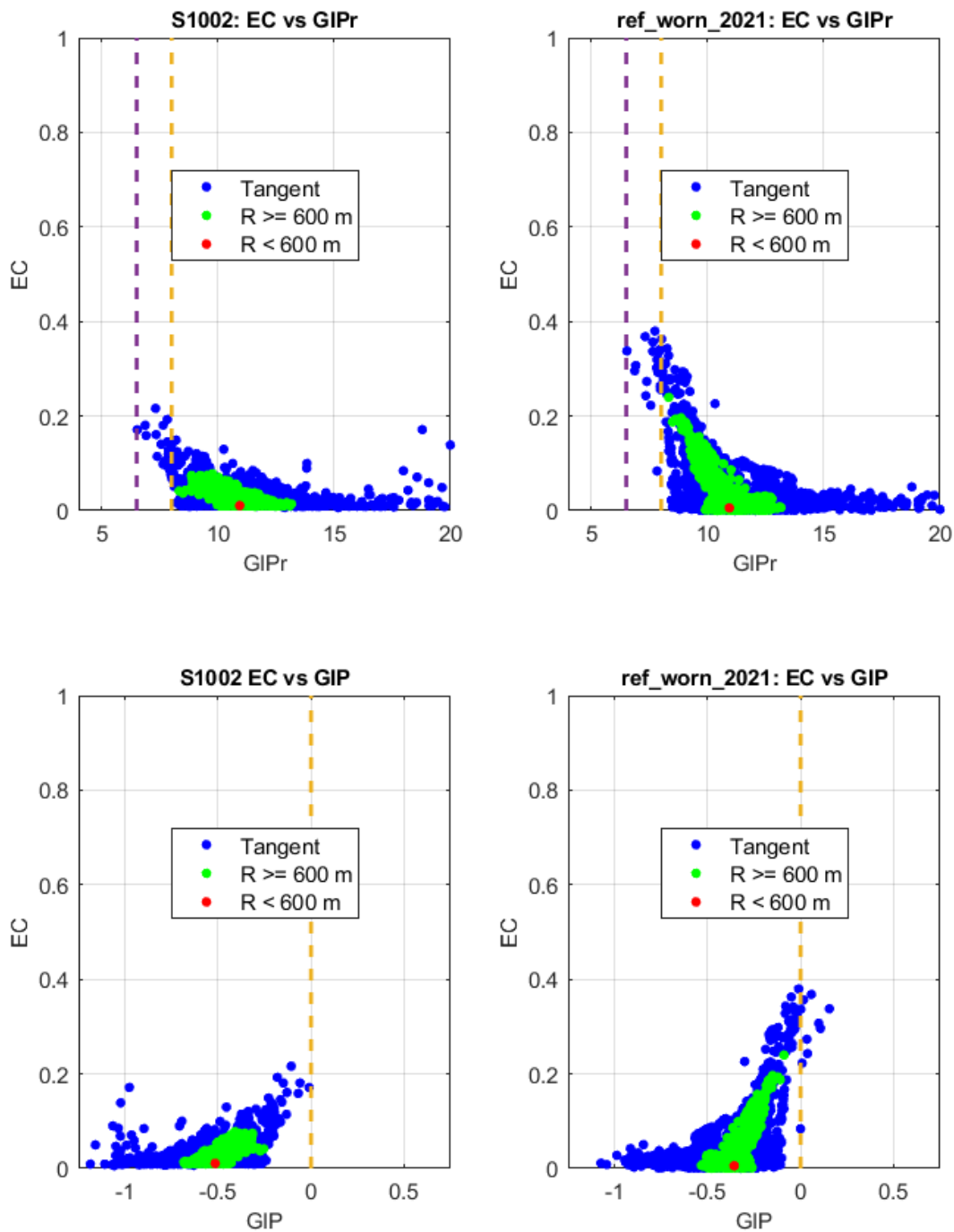


Figure 37. Results for Bdl 512U: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

## 4.6 Bdl 611: Falköping (F) – Alingsås (A)

Bdl 611, the track section connecting Falköping (F) and Alingsås (A) as depicted in Figure 38, consists of a ballasted double track dominantly employing 60E1 rail and concrete sleepers and includes numerous large and very large curves with radii ranging from 1,001 m up to 99,000 m. Bdl 611 has a relatively new superstructure with renewal activities since the 2000s.

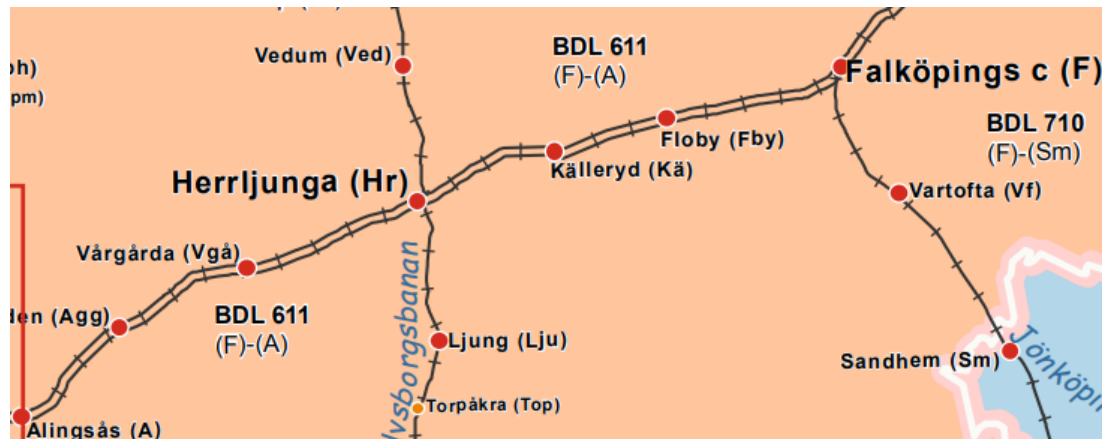


Figure 38. Bdl 611: Falköping (F) XXXX.

Figure 39 summarizes the results for Bdl 611N, including curvatures, track gauges (TG), equivalent conicities (EC S1102 and EC ref\_worn\_2021), Nonlinearity Parameters (NP), Gradient Index Profiles for Rail (GIPrL and GIPrR) and Gradient Index Profiles for combined wheel-rail (GIP S1002 and GIP ref\_worn\_2021). A few specific locations show EC ref\_worn\_2021 values exceeding 0.3 and GIPr values below GIPrAL. For the majority of the track locations, both track EC values with S1002 and in-service EC values with ref\_worn\_2021 are below the TSI INF limit 0.3.

In Figure 40, a summary of cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP is presented. Notably, although the differences between Zone A and Zone B can still be identified, they are much smaller than those in 410, 412 and 416. Additionally, there are still no results available for Zone C.

Figure 41 displays scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr. Similar trends are observed in Zone A and B, indicating strong correlations between EC and GIPr/GIP.

Similar observations and results for Bdl 611U are depicted in Figure 42, Figure 43 and Figure 44.

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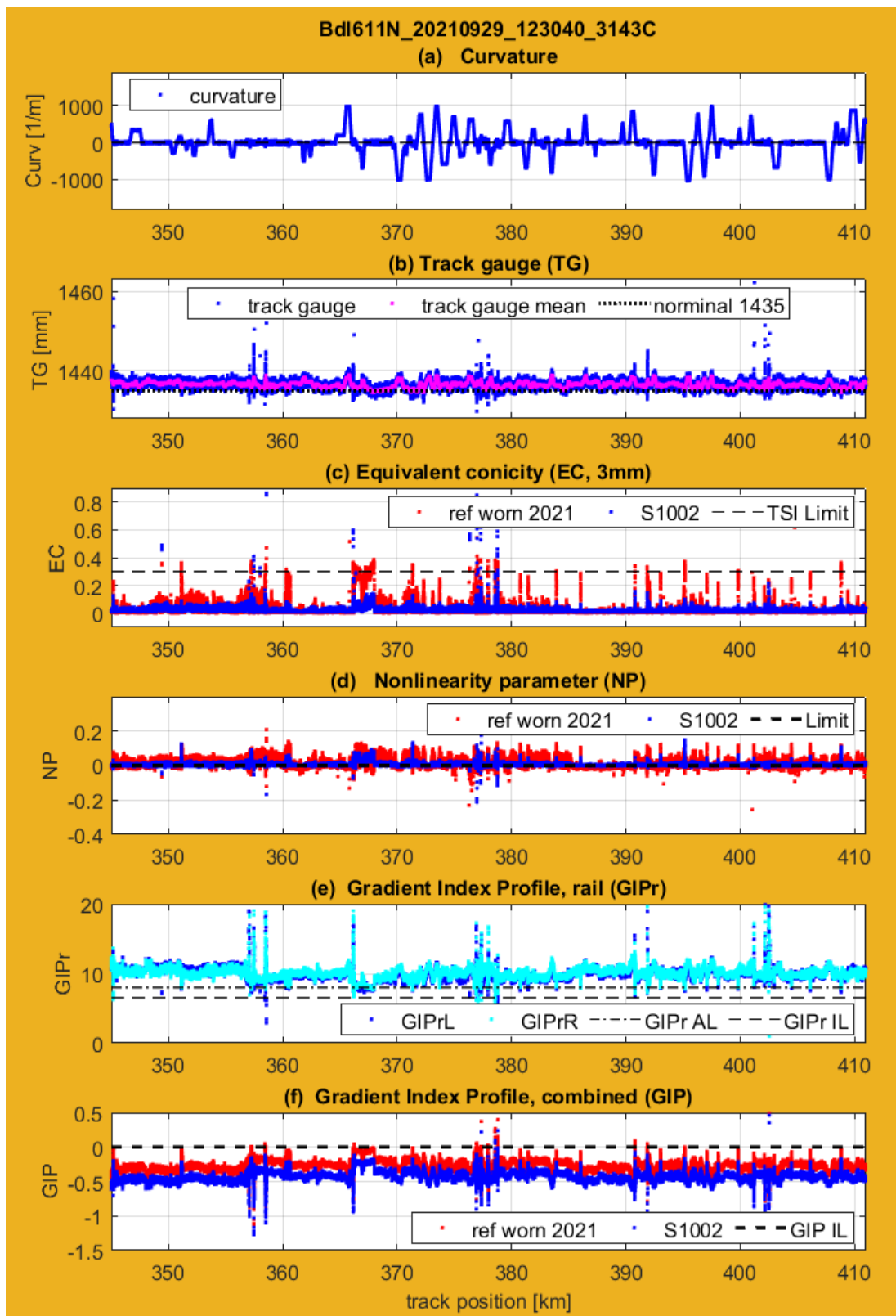


Figure 39. Results for Bdl 611N: (a). Curvature ([1/m] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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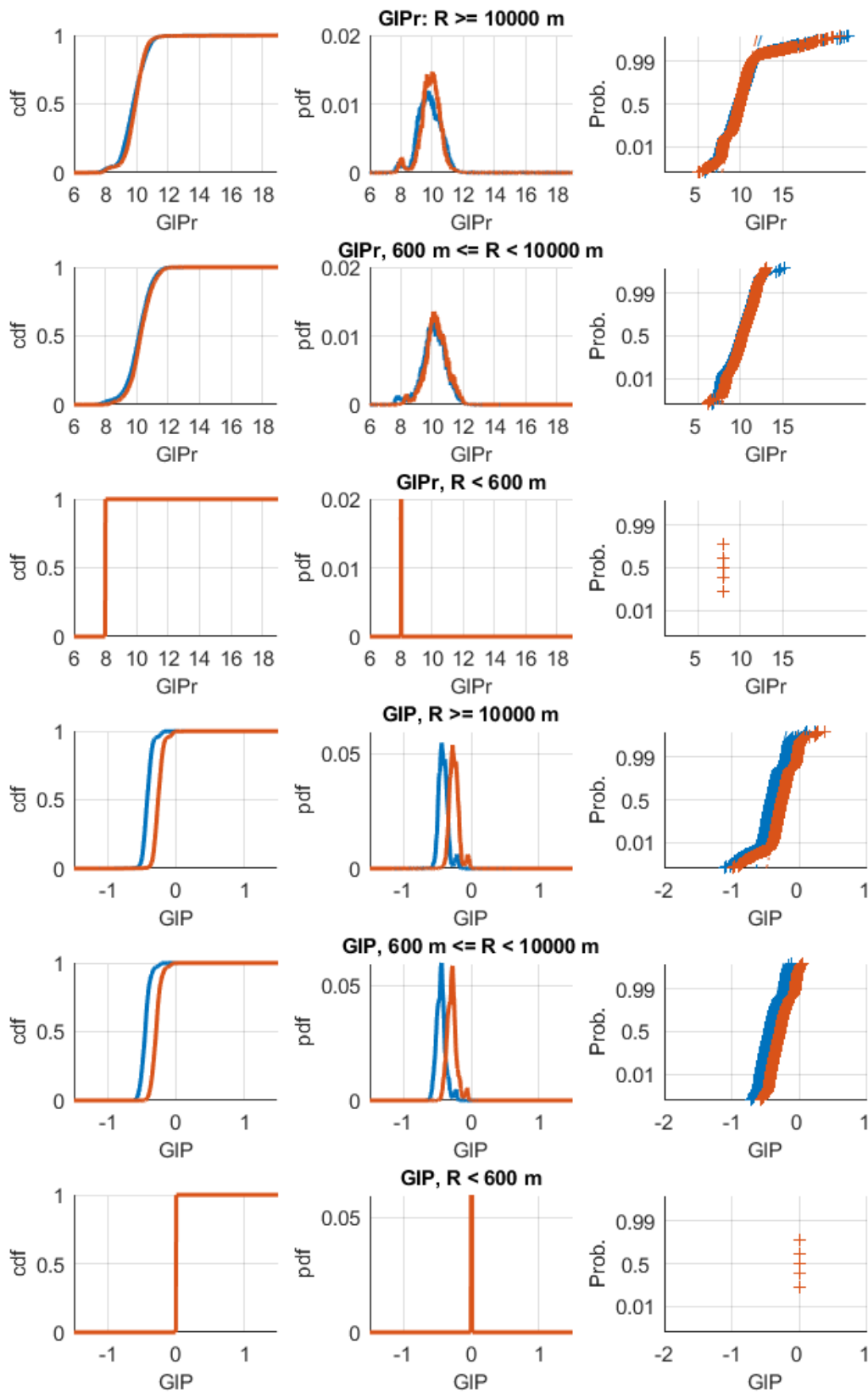


Figure 40. Results for Bdl 611N: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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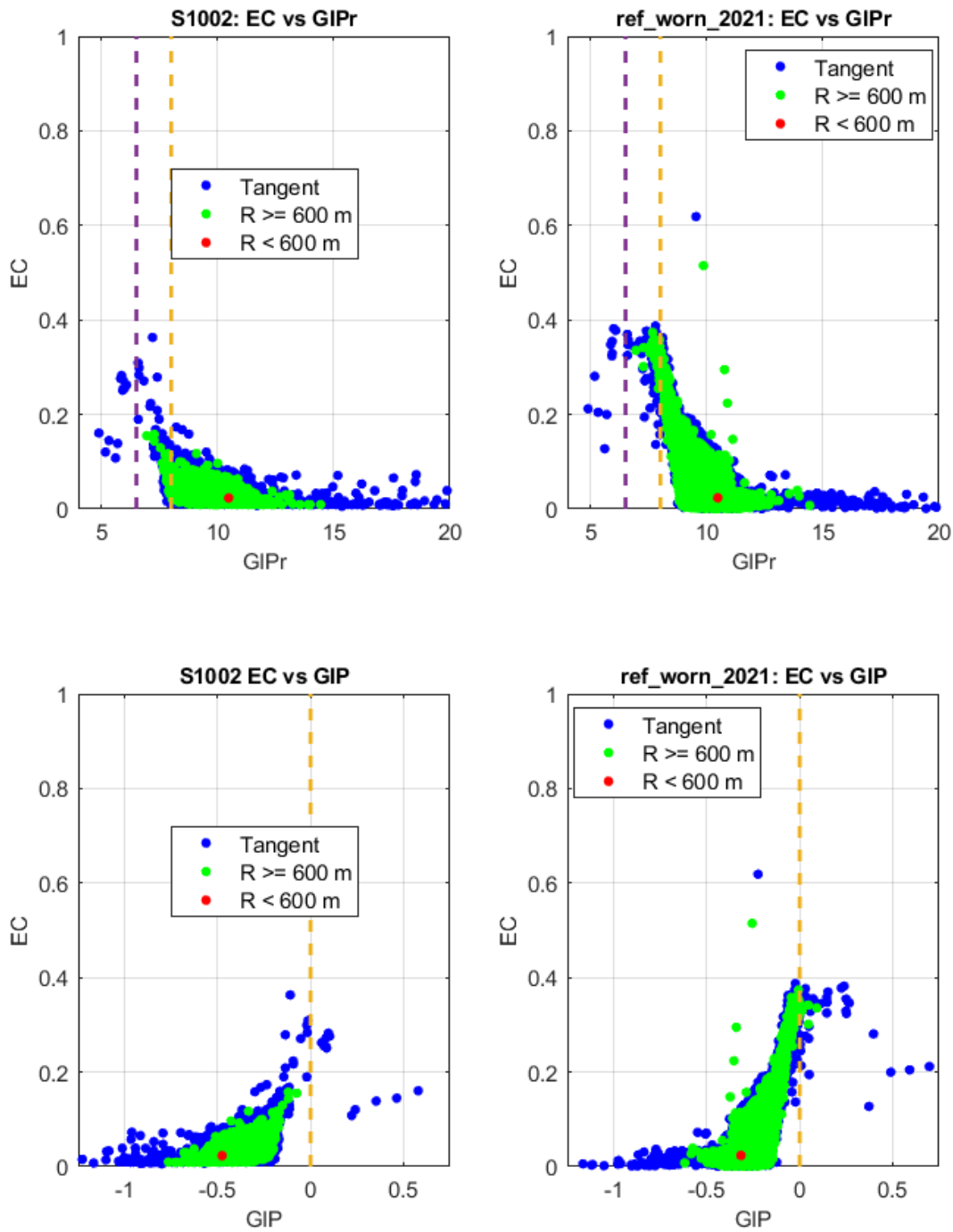


Figure 41. Results for Bdl 611N: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

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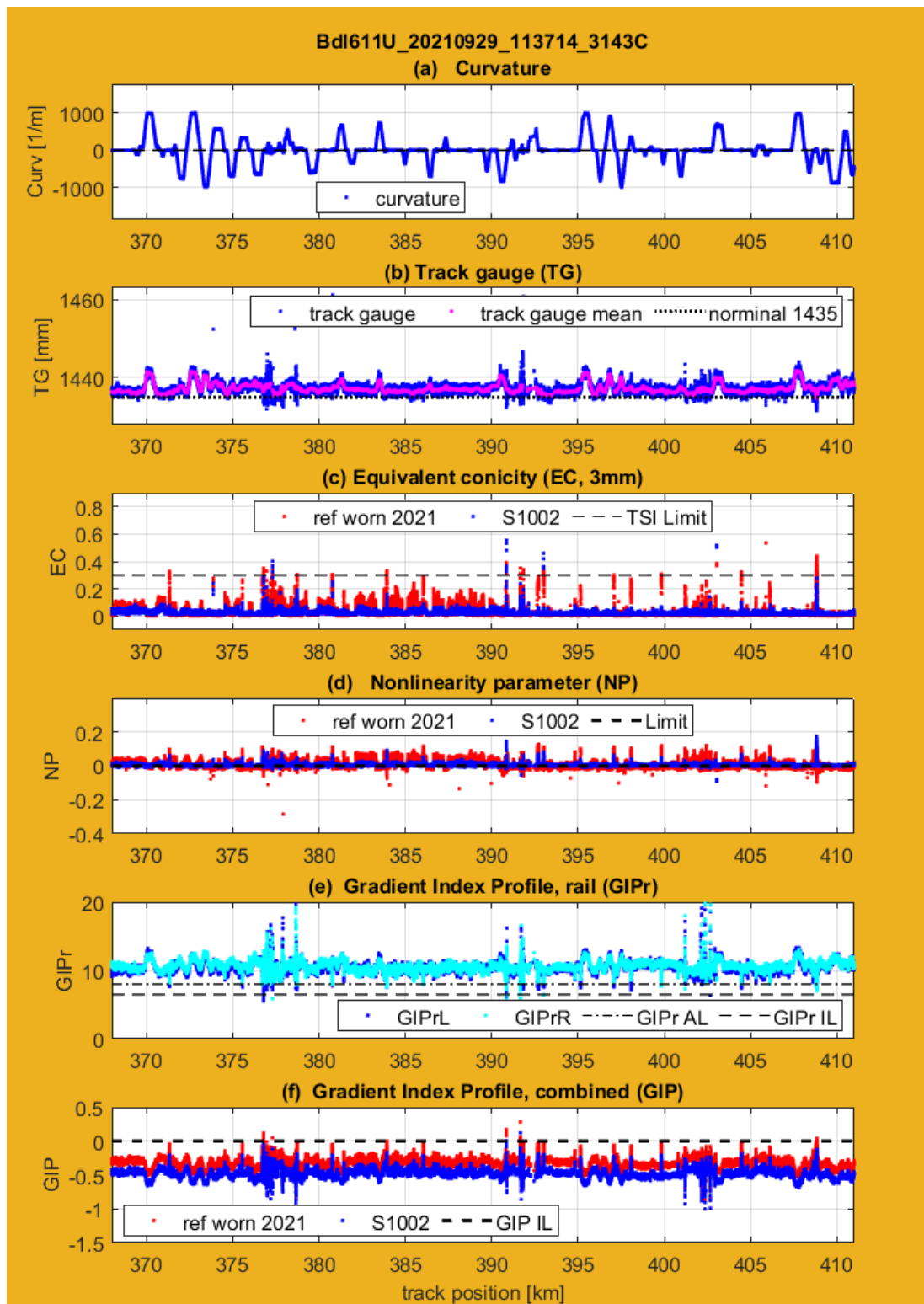


Figure 42. Results for Bdl 611U: (a). Curvature [ $1/m$ ] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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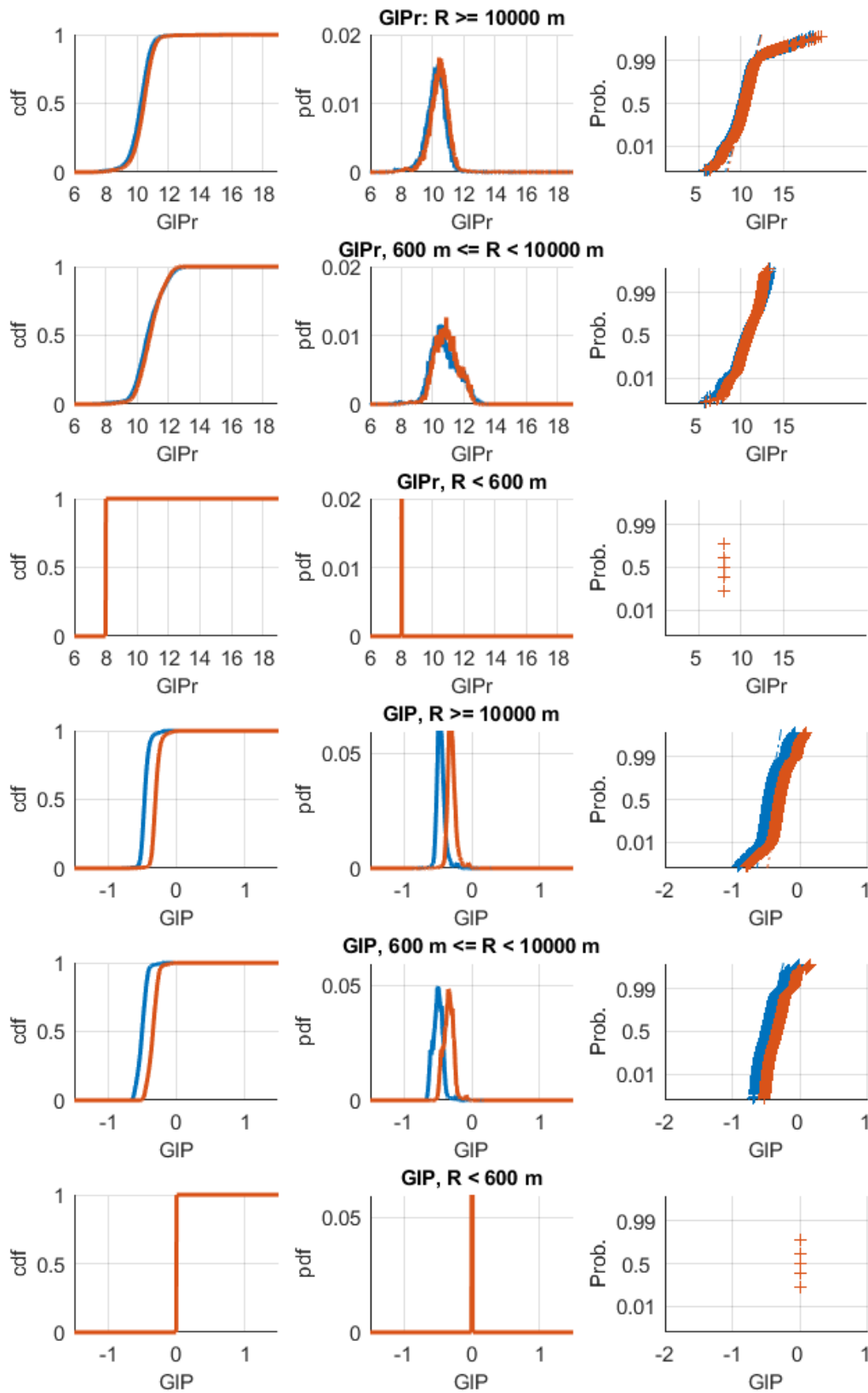


Figure 43. Results for Bdl 611U: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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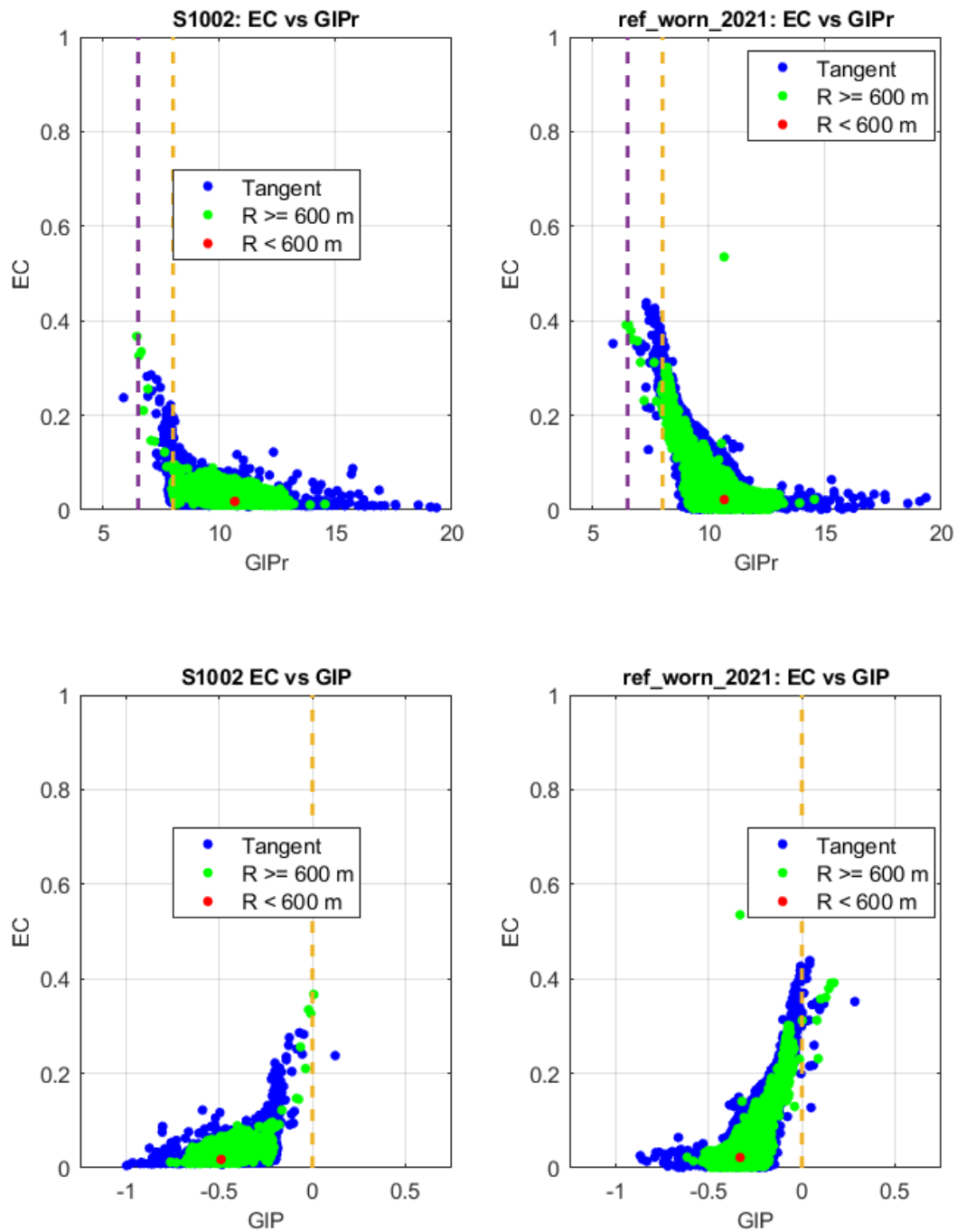


Figure 44. Results for Bdl 611U: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

## 4.7 Bdl 612 Alingsås (A) – Partille (P)

Bdl 612, the Bandel connecting Alingsås (A) and Partille (P) illustrated in Figure 45, consists of a ballasted double track primarily employing 60E1 rail and concrete sleepers, featuring numerous curves with radii ranging from 554 m up to 10,000 m. Bdl 612 has a relatively recent track superstructure, with rail renewal projects and rail surface maintenance actions (grinding) undertaken after the 2000s.

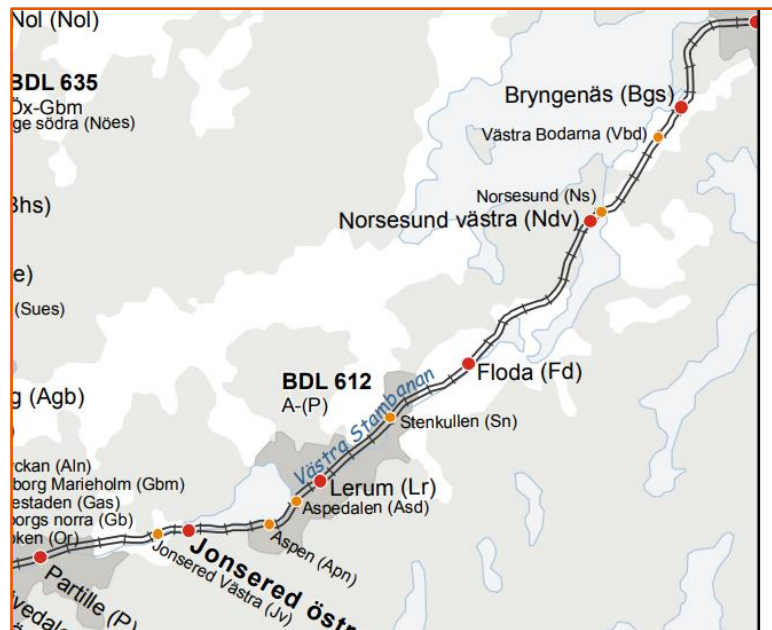


Figure 45. Bdl612 between Alingsås (A) and Partille (P)

Figure 46 presents the summarized results for Bdl 612N, including curvatures, track gauges (TG), equivalent conicities (EC S1102 and EC ref\_worn\_2021), Nonlinearity Parameters (NP), Gradient Index Profiles for Rail (GIPrL and GIPrR) and Gradient Index Profiles for combined wheel-rail (GIP S1002 and GIP ref\_worn\_2021). In the majority of track sections, both the track EC values with S1002 and the in-service EC values with ref\_worn\_2021 are below the TSI INF limit 0.3. However, a few specific track locations stand out, showing EC ref\_worn\_2021 values exceeding 0.3 and GIPr values falling below GIPrAL. These specific track locations warrant further investigation in the future.

In Figure 47, a summary of cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP is presented. Similar to the findings in Bdl 410, distinct differences are noticeable among Zones A, B and C. Notably, there are higher mean values of GIPr observed in smaller curves, prompting further investigation in the future.

Figure 48 displays scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr. Similar trends are observed in Zone A and B, indicating strong correlations between EC and GIPr/GIP.

Similar observations and results for Bdl 612U are depicted in Figure 49, Figure 50 and Figure 51.

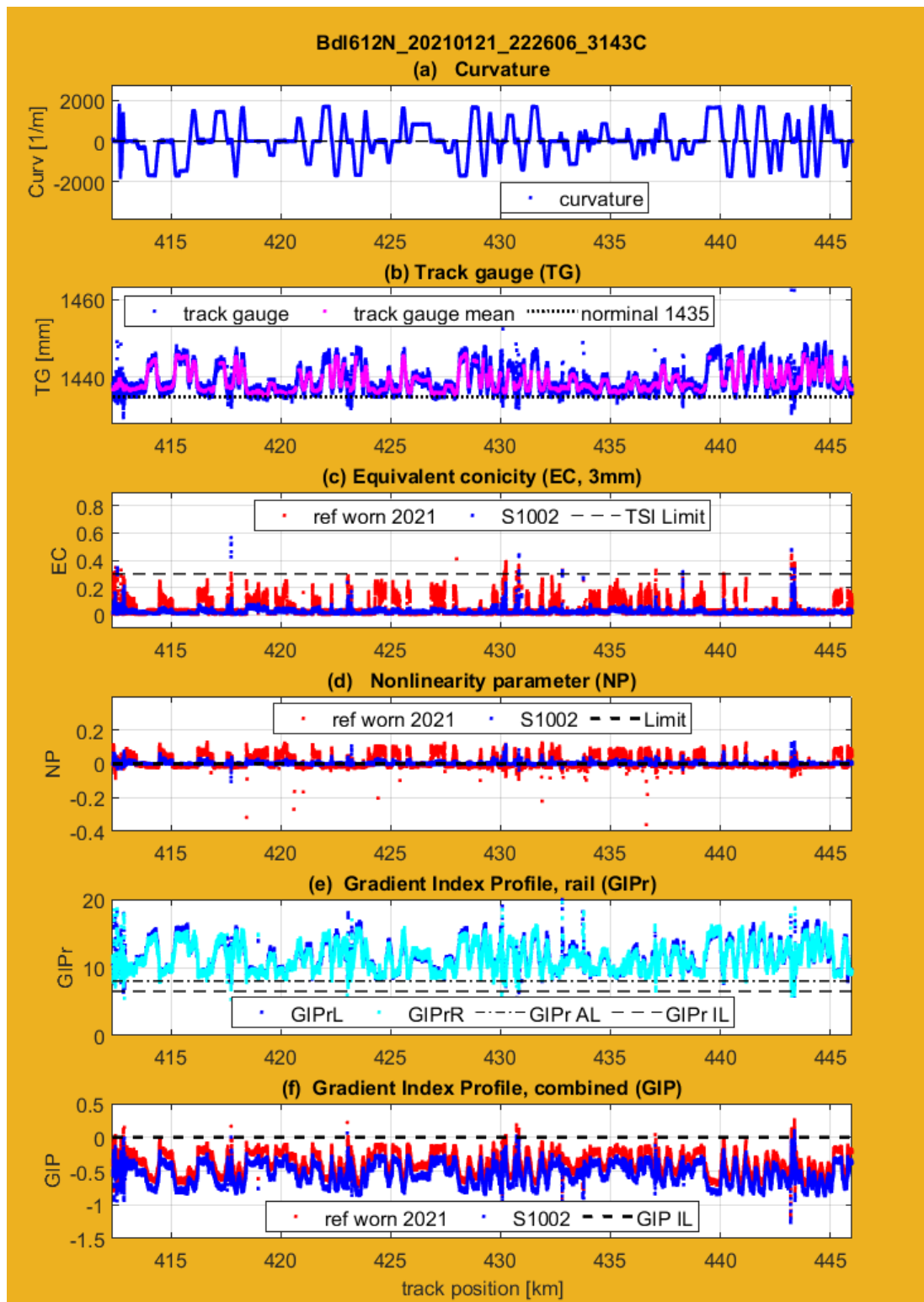


Figure 46. Results for Bdl 612N: (a). Curvature ([1/m] scaled), (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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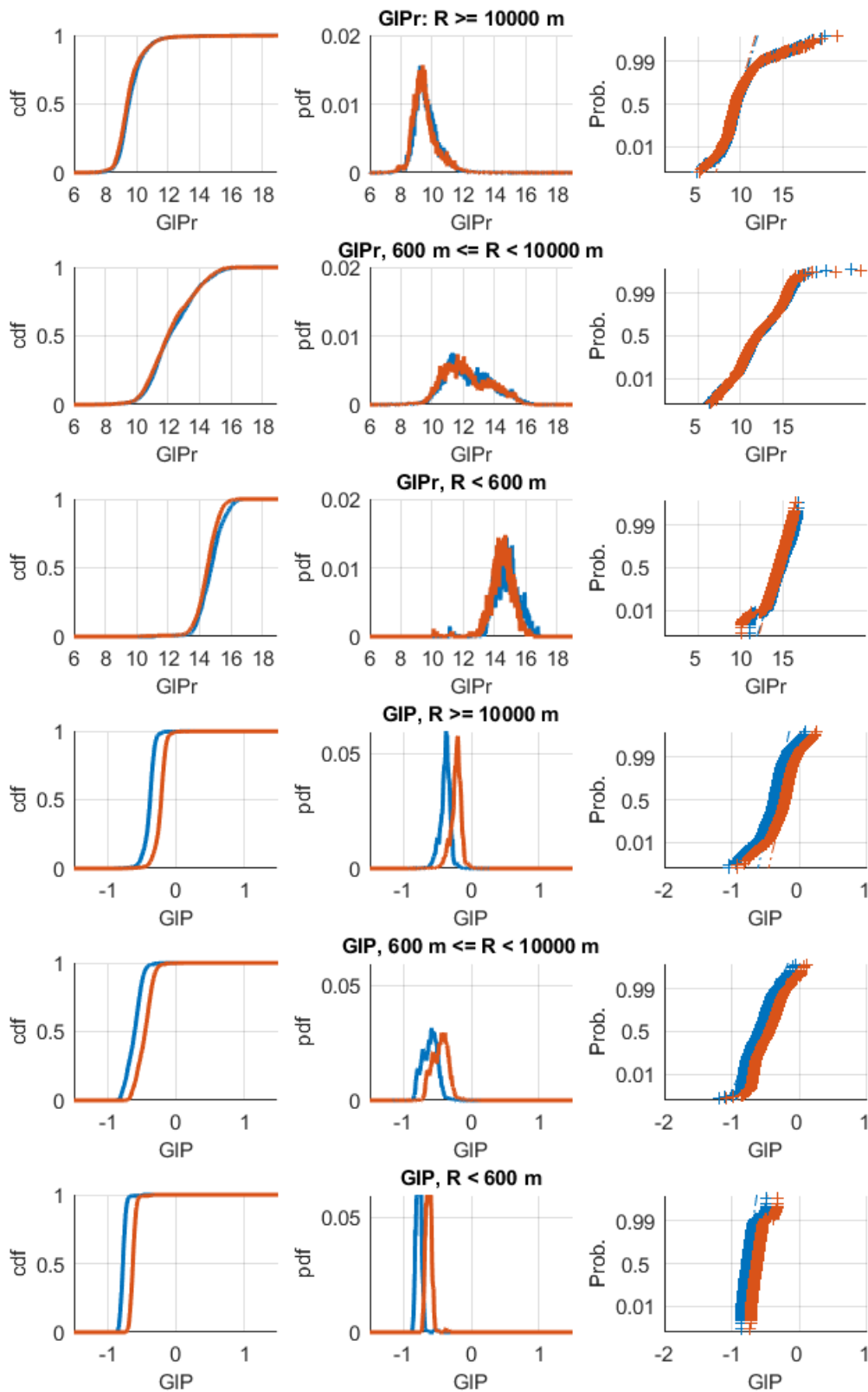


Figure 47. Results for Bdl 612N: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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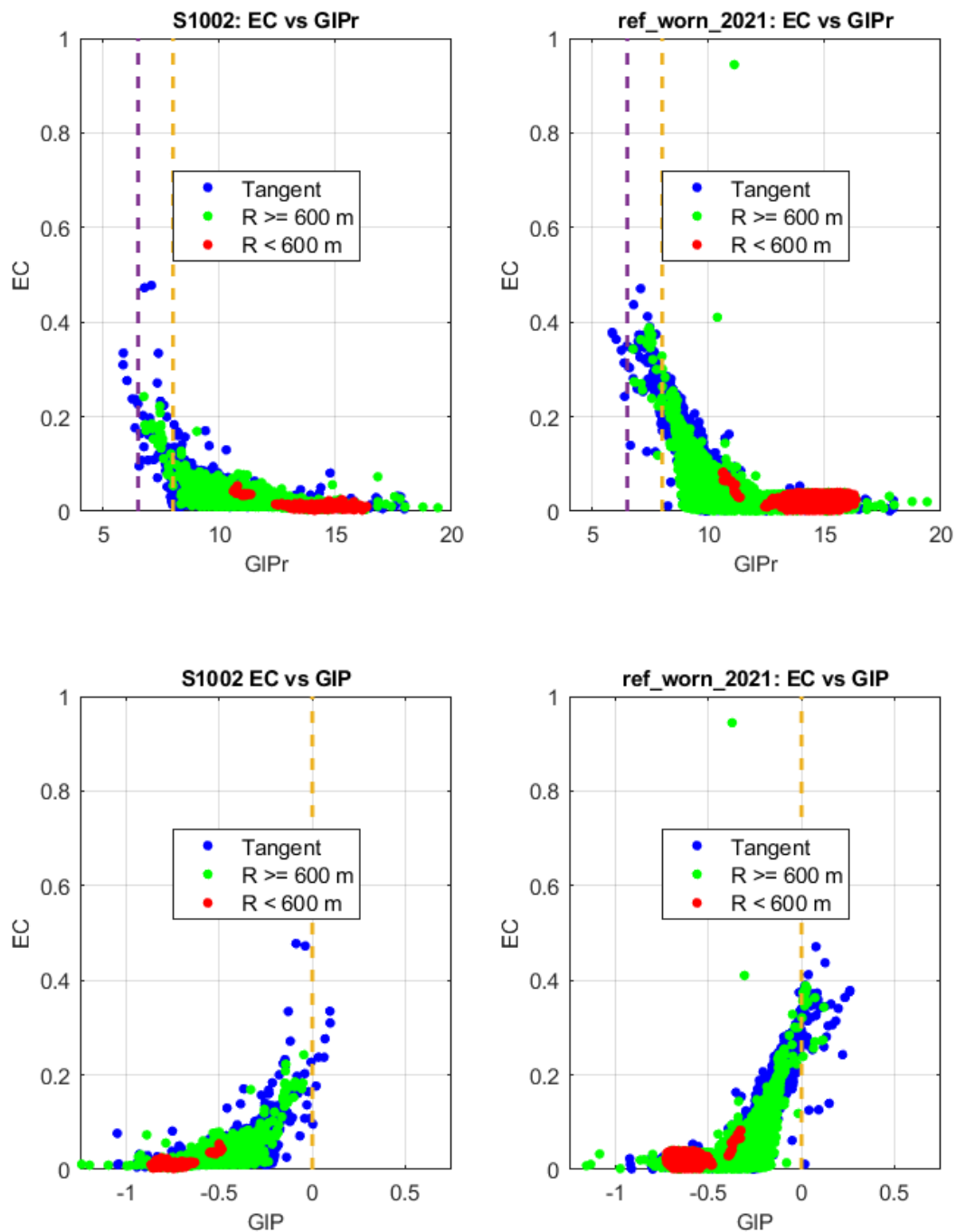


Figure 48. Results for Bdl 612N: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIPr for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

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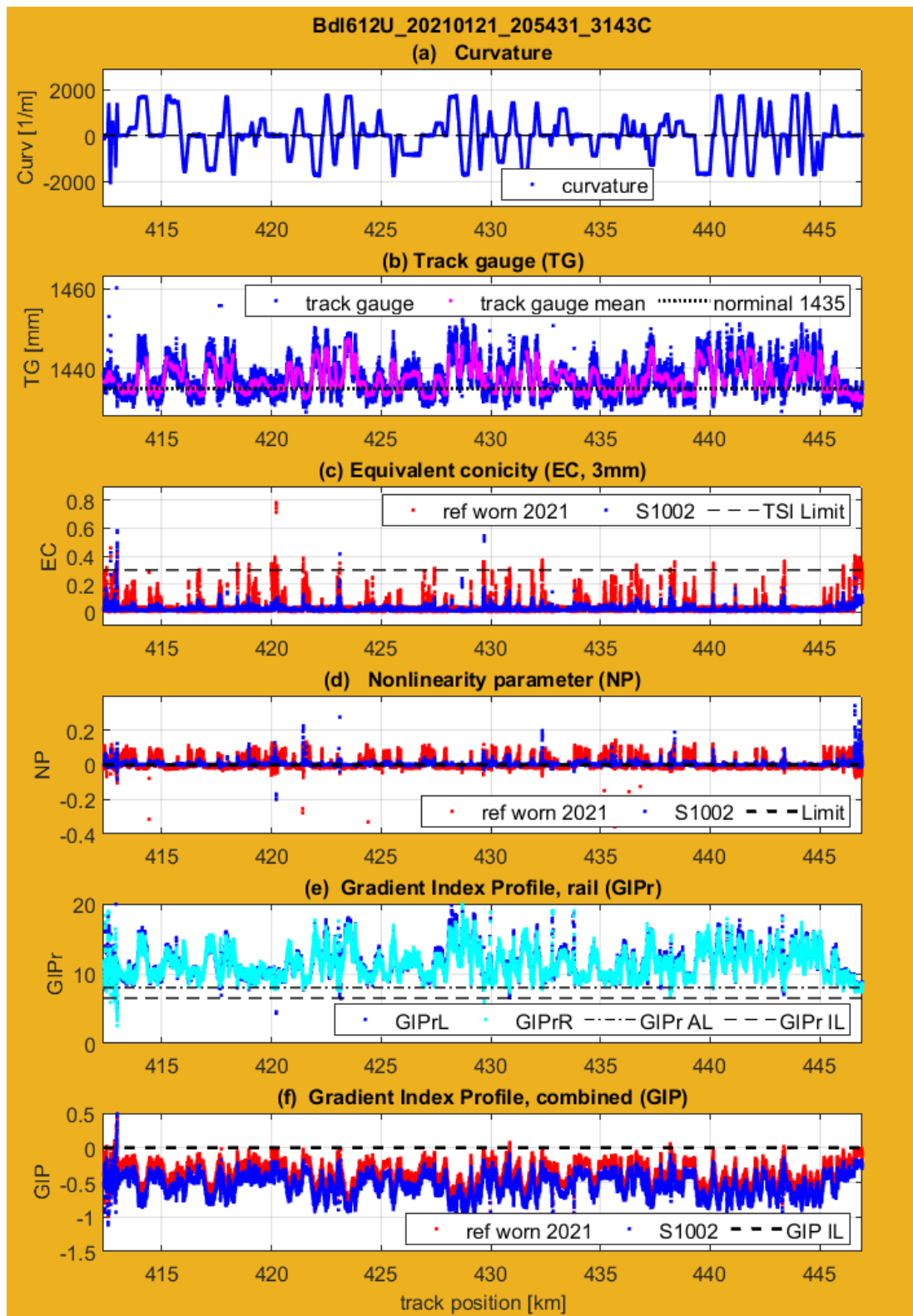


Figure 49. Results for Bdl 612U: (a). Curvature [ $1/m$ ] scaled, (b). Track gauge (TG) [mm], (c). Equivalent conicity with nominal S1002 profile (EC S1002) and in-service EC with the reference worn profile (EC ref. worn), (d). Nonlinearity parameter (NP S1002 and NP ref. worn), (e). Gradient Index Profile for rail (GIPrL, GIPrR) and (f). Gradient Index Profile Combined (GIP S1002 and GIP ref. worn).

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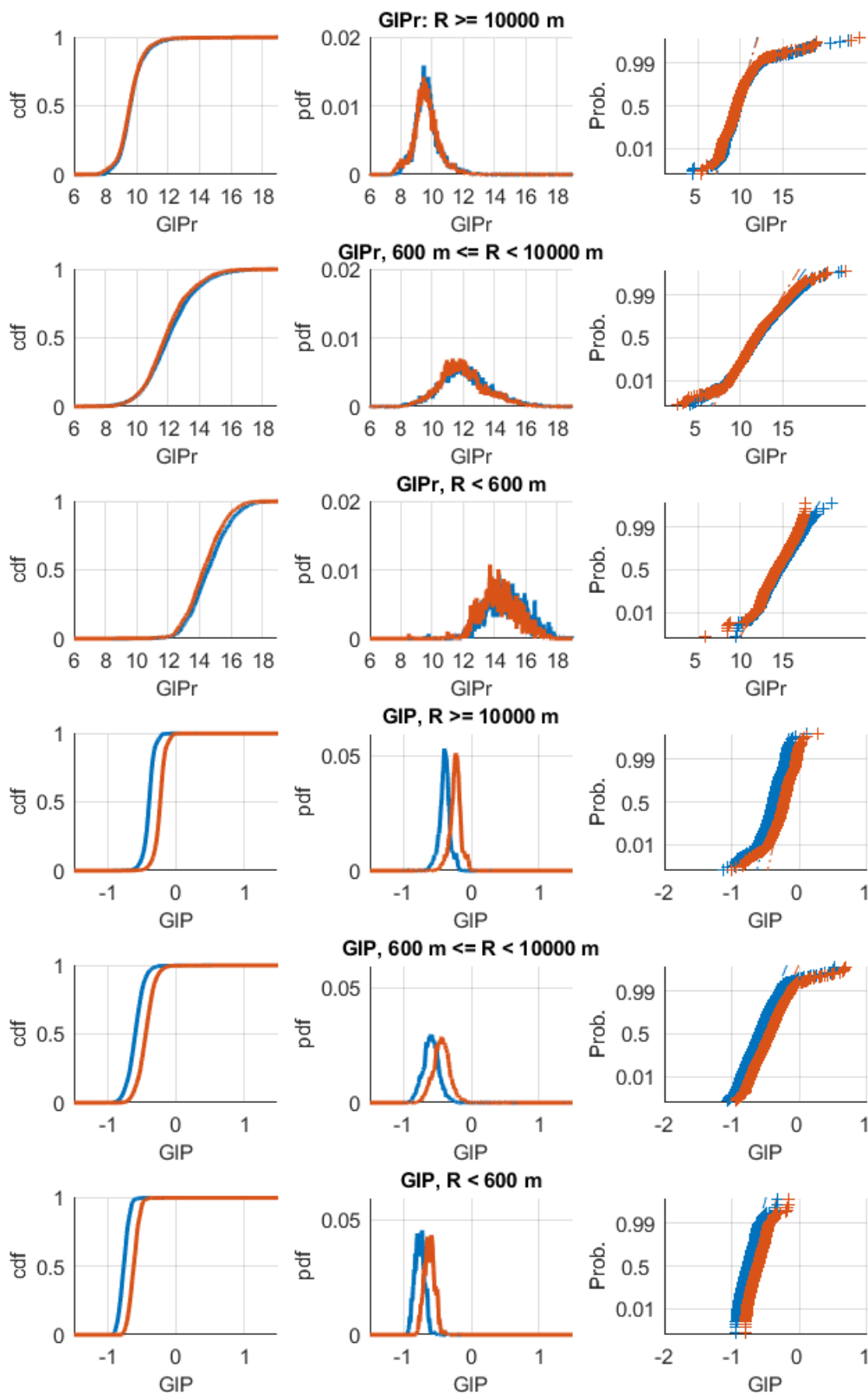


Figure 50. Results for Bdl 612U: cumulative distribution functions (cdf), probability density functions (pdf) and normal probability plots (prob.) for GIPr and GIP, grouped into three zones: A) tangent tracks with  $R \geq 10,000$  m; B) large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) small curves with  $R \leq 600$  m.

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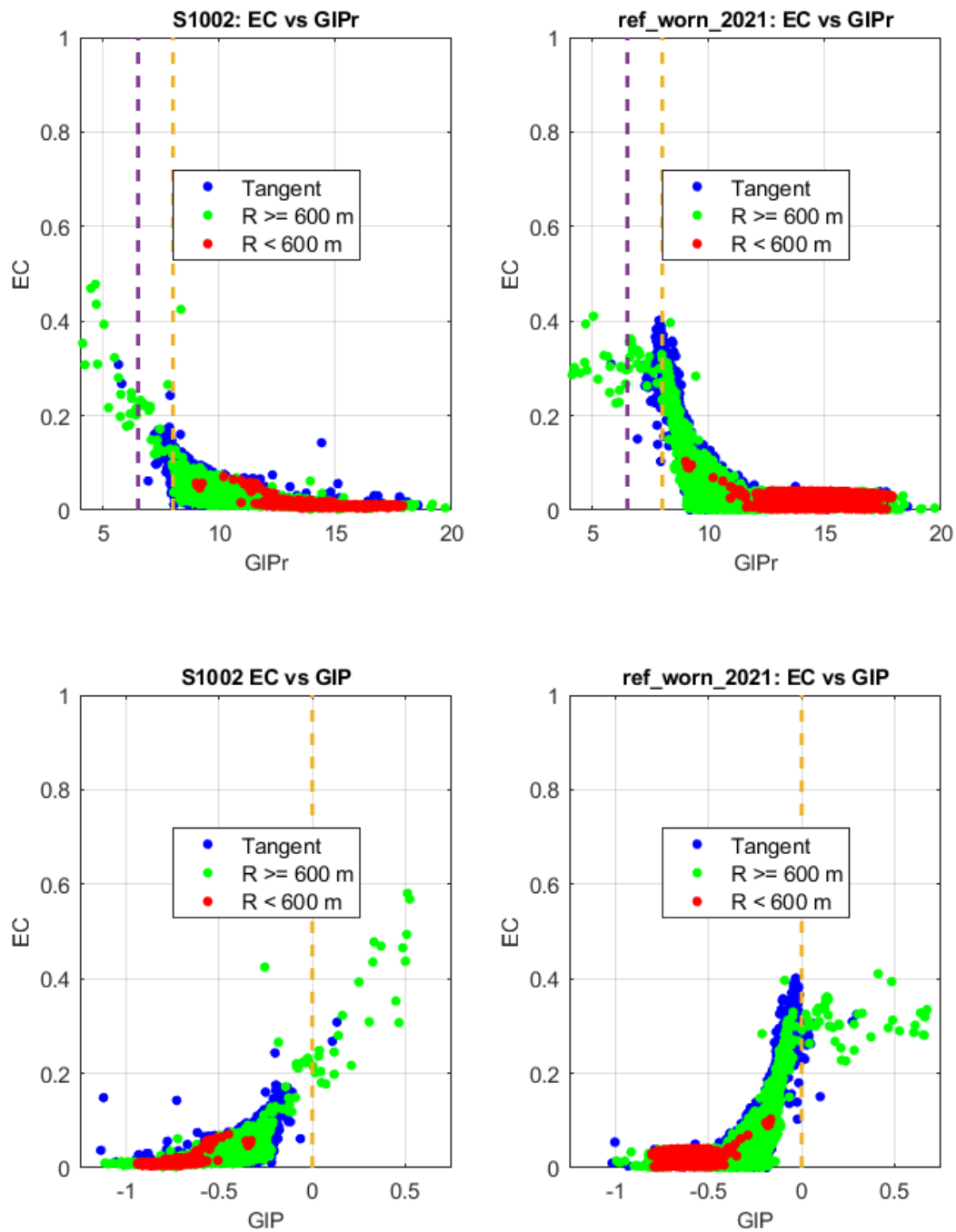


Figure 51. Results for Bdl 612U: scatter plots of EC S1002 vs GIPr, EC ref\_worn\_2021 vs GIPr, EC S1002 vs GIP and EC ref\_worn\_2021 vs GIP for three zones: A) Tangent track with  $R \geq 10,000$  m; B) Large curves with  $600 \text{ m} \leq R \leq 10,000$  m and C) Small curves with  $R \leq 600$  m.

## 5. Conclusions and future work

A comprehensive understanding of the wheel-rail geometric contact conditions along the Western Main Line in Sweden has been achieved through the investigations carried out in the project. Based on the results presented in this report and in the report 178508100-002, the following conclusions and recommendations are outlined:

- Generally, the wheel-rail contact geometry conditions on tangent tracks along the Swedish Western Main Line are quite good. In the majority of all parts of track sections, track gauges (TG) are not narrow, in-service equivalent conicity values (EC ref\_worn\_2021) remain below the TSI limit of 0.3, Nonlinearity Parameters (NP) values are positive, the GIPr values remain higher than the proposed GIPrAL and GIPrIL, and GIP values are negative. However, a few specific track locations stand out, where in-service EC values exceed 0.3, and GIPr values fall below GIPrAL. Investigating these identified track locations will be imperative in our future activities.
- The distribution functions of GIPr exhibit clear distinctions between tangent tracks and curves. Notably, smaller curves, such as those in Bdl 410 and 612, display higher mean and variance values. Further studies are warranted to understand the corrections between GIPr (GIPw and GIP) and other parameters related to wear and/or RCF.
- In Bdl 511 and 512 tangent tracks, we observe very low values of in-service equivalent conicity and distinct distributions between GIPrL and GIPrR. These findings demand further investigation.
- To monitor the evolution of wheel-rail contact conditions along the Western Main Line, on-track results for GIPr, GIP and EC based on new measurements conducted in 2022 and 2023 will be evaluated.

## 6. Acknowledgements and disclaimer

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This document reflects the views of the author(s) and does not necessarily reflect the views or policy of the European Commission. Whilst efforts have been made to ensure the accuracy and completeness of this document, the IN2TRACK2 and IN2TRACK3 consortiums shall not be liable for any errors or omissions, however caused.

## 7. References

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## 8. Revisions

Revision	Date	Description
1	2024-02-27	First issue.