MONITORING TRAIN PERFORMANCE IN CASE OF LOW ADHESION;

ACQUIRING KNOWLEDGE FOR THE DEVELOPMENT OF LOW ADHESION MEASURES

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PhD Thesis

By Niels van Steenis at the Faculty of Engineering Technology (CTW) of the University of Twente, Enschede, the Netherlands.

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Cover:

Typical location that is troubling by low adhesion by leafs in autumn; a lot of trees along the track.

Samenvatting

De gladde sporen problematiek is inherent aan het gekozen principe van het versnellen (aanzetten) en vertragen (remmen) van een trein door middel van een stalen wiel op een stalen rail. Het voordeel van een lage rolweerstand heeft als nadeel dat de rem- en aandrijfkrachten die overgebracht worden door een (rond) wiel op de rail beperkt zijn. Als van de wielen een hogere kracht wordt gevraagd dan ze kunnen overbrengen op het spoor gaan de wielen slippen, dit kan zowel bij het versnellen van de trein als bij het vertragen. Al sinds tenminste 150 jaar wordt onderzocht hoe deze krachtoverdracht verbeterd kan worden. Dit heeft geresulteerd in al meer dan een miljoen wetenschappelijke publicaties over dit onderwerp. Er zijn al een groot aantal maatregelen ontwikkeld maar ondanks dat is er nog steeds overlast door gladheid.

De laatste decennia wordt het verbeteren van deze krachtsoverdracht alleen maar belangrijker omdat er wens is naar sneller, efficiënter (beter benutten spoorcapaciteit) en veiliger vervoer. Vanwege dit belang hebben NS en ProRail het gladde sporen onderzoeksprogramma AdRem (Adhesie Remedie) opgestart. Onderleiding van NS en ProRail hebben Universiteit Delft, Wageningen Universiteit en Universiteit Twente met ondersteuning van Lloyd's Register Rail en Delta Rail dit onderzoeksprogramma uitgevoerd. Het onderzoek waar dit document betrekking op heeft is in het kader van AdRem uitgevoerd.

Gladheid heeft met name negatieve gevolgen voor punctualiteit, spoorcapaciteit, veiligheid, schade aan materieel/infrastructuur en imago. Basiskennis over gladheid is maar beperkt bekend zoals: waar en wanneer is het hoe glad, welke rem-/aanzetprestaties kan een trein halen op glad spoor, hoe vaak treedt gladheid op, hoe bedient de machinist de trein bij gladheid, wat zijn de gevolgen van gladheid op de punctualiteit, veiligheid en spoorcapaciteit. De kennis die wel bekend is is voor het overgrote deel gebaseerd op subjectieve waarneming van met name machinisten.

Het gebrek aan kennis over de problematiek is een belangrijke reden dat het gladde sporen probleem nog steeds bestaat. Hierdoor is het lastig om effectieve en efficiënte maatregelen te nemen. Oorzaak van de gebrekkige kennis over gladheid is het gebrek aan een meetmiddel dat de problematiek zoals die in de praktijk voorkomt kan vaststellen. Dit meetmiddel moet niet alleen in staat zijn om gladheid te meten, maar ook verbanden kunnen leggen tussen gladheid en locatie, tijdstip, genomen maatregelen, treinprestaties en bediening door machinist. Om deze verbanden goed in kaart te brengen is het noodzakelijk om veel metingen uit te voeren.

De doelstelling van dit onderzoek is is het inzichtelijk maken van de problematiek en op basis daarvan verbetervoorstellen op te stellen.

Om de gewenste inzichten te verkrijgen zijn 5 meettreinen (VIRM tribotreinen) ontwikkeld. Deze meettreinen kunnen de mate van gladheid meten als er slip van één van de aangedreven assen optreedt. Omdat de motoren ook worden benut om te remmen kan niet alleen bij aanzetten, maar ook bij remmen gladheid worden gemeten. Voor het bepalen van de gladheid is een algoritme ontwikkeld dat op basis van reeds aanwezige meetgegevens in de trein de mate van gladheid kan vaststellen. Een proof of principle heeft uitgewezen dat het mogelijk is om gladheid op deze manier te meten. Helaas was de nauwkeurigheid van de 5 VIRM tribotreinen bij de beproevingen in de praktijk een stuk lager dan bij de proof of principle. Deze lagere nauwkeurigheid heeft negatieve gevolgen gehad voor een gedeelte van het onderzoek.

Naast het meten van de mate van gladheid kunnen de VIRM tribotreinen het volgende meten: locatie, tijdstip, geleverde motorkoppel, aslast, wielslip [ja/nee], gevraagde motorkoppel, treinsnelheid en magneetrem ingeschakeld. Met deze meetgegevens kunnen de gewenste verbanden worden gelegd. Het overgrote deel van de meetgegevens is afkomstig uit het reeds in de trein aanwezige diagnosesysteem. Omdat geen complexe meetapparatuur aangebracht hoeft te worden kan gemeten worden vanuit een reizigerstrein in de dienst. Hierdoor is het mogelijk om veel metingen uit te voeren. De meetgegevens worden door middel van GSM overgezonden naar een computer op de wal die de gewenste analyses uitvoert.

De 5 VIRM tribotreinen hebben gemeten van 30 januari 2008 tot en met 30 januari 2009. Om het verloop van de gladheid in de tijd te kunnen onderzoeken is het noodzakelijk dat er een aantal metingen per dag worden uitgevoerd op een bepaalde locatie. Daarom is er voor gekozen om de meettreinen gedurende de herfst in te zetten op een vasttraject (Den Helder-Nijmegen).

Op basis van de meetgegevens zijn analyses uitgevoerde die de volgende inzichten hebben gegeven:

- In de herfst treedt veel meer gladheid op dan buiten de herfst; maar ook buiten de herfst komt gladheid met een lage wrijving en/of over grote lengte voor.
- Binnen de herfst kunnen er van dag tot dag grote verschillen optreden.
- Gladheid kan optreden over tientallen kilometers lengte.
- Er zijn locaties (regio's) waar regelmatig gladheid optreedt; er zijn ook locaties (regio's) waar zelden of nooit gladheid optreedt.
- Gesignaleerd is dat als er gladheid optreedt op een bepaalde locatie het over het algemeen optreedt op het heen- en het teruggaande spoor.
- Extreme gladheid kan zeer snel (binnen een uur) in de tijd ontstaan.
- Het is aannemelijk gemaakt dat gladheid een belangrijk aandeel heeft in de punctualiteitdip in de herfst.
- Remsysteem van het VIRM-materieel is gedurende de meetperiode nagenoeg adequaat gebleken om uitschieters door gladheid te voorkomen. Gladheid leidt voor het VIRM-materieel tot een laag veiligheidsrisico.
- Het rijtijdverlies in de herfst ontstaat voor ongeveer ¾-deel op de eerste kilometer van een traject bij het versnellen en voor ongeveer ¼-deel op de laatste kilometer van een traject bij het afremmen.
- Op een glad traject (< 10 km) kan het rijtijdverlies door gladheid oplopen tot ongeveer 2 minuten.
- Machinisten passen hun rijgedrag aan op gladspoor zowel bij remmen als aanzetten en beïnvloeden hiermee de rijtijd (punctualiteit). Bij onderzoek naar inzet van maatregelen ter vermindering van overlast door gladheid zal het gedrag van de machinist deel moeten uitmaken.
- Het bestaande gladheidvoorspellingsmodel is alleen geschikt om machinisten te melden dat zij op een bepaalde dag extra alert moeten zijn voor gladheid (een alertheidswaarschuwing). Het is niet goed genoeg om machinisten met grote

betrouwbaarheid te waarschuwen of op basis van de waarschuwing maatregelen in te zetten.

- Met name voor de tractiebesturing en in mindere mate voor de ABI is er een groot verbeterpotentieel aanwezig om de aanwezige adhesie optimaal te benutten. Hierdoor kunnen de aanzet- en remprestaties op glad spoor sterk verbeteren.
- De ontwikkelde methode voor prestatiemonitoring kan ook voor andere onderwerpen benut worden.
- Sandite werkt niet zodanig dat na het aanbrengen er de gehele dag geen gladheid meer optreedt. Op ongeveer de helft van de dagen wordt Sandite onnodig aangebracht.
- Het is niet gelukt om inzicht te verwerven in de effectiviteit van magneetremmen.

In het kader van dit onderzoek is een methode ontwikkeld waarmee inzicht kan worden verkregen in de effectiviteit van maatregelen. Aangetoond is dat deze methode werkt door toepassing van deze methode op de maatregelen Sandite en magneetremmen. Om een definitief inzicht te hebben in de effectiviteit van deze maatregelen zijn meer metingen op glad spoor nodig en is een hogere sample frequentie van de VIRM tribotreinen vereist. Het kennen van de effectiviteit van maatregelen op gladheid zoals dat in de praktijk voorkomt is erg belangrijk. Het is dan mogelijk om kosten baten afwegingen te maken van maatregelen en het is mogelijk om maatregelen te optimaliseren.

Op basis van het grote aantal verkregen inzichten kan gesteld worden dat het principe van de VIRM tribotreinen in combinatie met de gekozen inzet en analysemethodes een krachtig middel is om inzicht te krijgen in de problematiek (prestatiemonitoring).

Op de opgedane kennis kunnen de volgende aanbevelingen/verbetervoorstellen gedaan worden:

- Geconstateerd is dat gladheid op wisselende locaties en tijdstippen op kan treden. Vanuit oogpunt van kosten en efficiency moeten maatregelen daarom een hoge mate van flexibiliteit bezitten. Maatregelen op iedere trein hebben daarom de voorkeur boven maatregelen vanuit de baan.
- Beproeven van maatregelen met de ontwikkelde methodes. Op basis van de onderzochte effectiviteit van maatregelen kan besloten worden al dan niet te investeren. Meest voor de handliggende maatregelen zijn: magneetremmen, zandstrooiers, verbeteren tractiebesturing en Sandite.
- Het voorspellingsmodel kan worden verbeterd door de voorspelde gladheid te vergelijken met de gemeten gladheid; hierdoor ontstaat een terugkoppellus.
- De Sandite campagne kan worden verbeterd door alleen Sandite aan te brengen op dagen dat het echt nodig is. Weten of het echt nodig is kan op basis van het verbeterde voorspellingsmodel.
- De tractiebesturing en in mindere mate de ABI zijn vatbaar voor verbetering. Door betere benutting kunnen de aanzet- en remprestaties op gladspoor sterk verbeteren.

- Bij het bestellen van nieuw materieel moet met de volgende aspecten rekening gehouden worden:
    - Hoeveel aangedreven assen en magneetremmen zijn noodzakelijk om de gewenste rem- en aanzetprestaties te leveren.
    - De wenselijkheid om nieuw materieel te voorzien van zandstrooiers.
    - Welke parameters moet het diagnosesysteem meten en is het verstandig om alle treinen te voorzien van een boord-wal-verbinding zodat alle informatie die in de trein aanwezig is ook op de wal bekend is.
- Onderzoeken waarom machinisten hun rijgedrag bij aanzetten aanpassen. Als het onderzochte rijgedrag afwijkt van wat een optimale aanzetprestatie oplevert wordt aangeraden machinisten nieuw rijgedrag aan te leren.
- Met de ontwikkelde methode de remweg en de remwegverdeling vaststellen van alle in Nederland aanwezige treintypen. Deze gegevens zijn van groot belang voor het bepalen van een optimale (maar nog net veilige) benutting van het spoor.

De gladde sporen problematiek is een complex probleem dat beïnvloed wordt door zeer veel factoren. In dit proefschrift zijn de factoren en de verbanden tussen deze factoren beschreven.

Samengevat kan geconcludeerd worden dat door dit onderzoek de problematiek (inzichtelijk) meetbaar is gemaakt. De waarnemingen zijn gebaseerd op objectieve metingen in plaats van op subjectieve waarnemingen. Door dit onderzoek is duidelijk geworden hoe gladheid zich in de praktijk voordoet; de problematiek is begrijpelijk gemaakt. Op basis van dit inzicht/begrip is het mogelijk gebleken om een groot aantal verbetervoorstellen te formuleren. Tevens kan door prestatiemonitoring vastgesteld worden of de problematiek is verminderd nadat maatregelen zijn genomen.

Summary

The problem of slippery tracks is inherent to the applied method of accelerating (traction) and decelerating (braking) a train by wheels of steel on a steel track. The advantage of a low rolling resistance is accompanied by the disadvantage that the forces, which are transmitted by a (round) wheel to the track, needed for driving and braking are limited. If the wheels have to deliver a higher force to the rail than they can transmit, the wheels start to slip. Slipping is possible in both acceleration and deceleration. For at least 150 years now, research has been conducted on how to improve the force transmission. This has resulted in over one million scientific publications on this subject (reference [1]). A large number of measures have been developed; nevertheless trouble caused by low adhesion still occurs.

The need for faster, more efficient (improved utilization of the track capacity) and safer transportation over the past decade, has made it increasingly important to improve the transmission of force. As a result thereof, NS and ProRail have initiated the low adhesion rail research program AdRem (Adhesion Remedy). Under supervision of NS and ProRail, the University of Delft, Wageningen University and the University of Twente conducted this research program together with the support of Lloyd’s Register Rail and Delta Rail. The research that this document refers to has been conducted within the scope of AdRem.

Low adhesion mainly has negative consequences for punctuality (driving on time), track capacity, safety, damage to rail/rolling stock and image. Basic knowledge about low adhesion is only limitedly available, such as where and when is low adhesion and to what extent, what braking/acceleration performance can a train achieve on the tracks, how often does low adhesion occur, how does the driver operate the train in case of low adhesion, what are the consequences of low adhesion for punctuality (driving on time), safety and track capacity. The available knowledge is largely based on subjective observations, for the most part offered by drivers.

A lack of knowledge about the problem is an important reason why slippery tracks are still a problem. This makes it difficult to take effective and efficient measures. The lack of knowledge on low adhesion is a result of the absence of a measurement tool that can establish the problem as it occurs in practice. This measurement tool must not only be capable of measuring low adhesion, it must also be able to make relations between low adhesion, time, measures taken, train performance and driver’s operation. In order to properly chart these connections many measurements need to be conducted.

This research aims at finding insight into the problem and being able to draw up suggestions for improvement based on the findings.

In order to acquire the desired insight, 5 measurement trains (VIRM tribo trains) were developed. These measurement trains can measure the extent of low adhesion when slipping occurs on one of the driven axes. Because the traction installations (engines) are also used for braking, low adhesion can be established during acceleration as well as during braking. In order to determine low adhesion a algorithm has been developed that can establish the extent of the low adhesion based on information already available on the trains. A proof of principle showed that it is possible to measure low adhesion using this method. Unfortunately the accuracy of the 5 VIRM tribo trains used during the test (in service) was much lower than the accuracy in the proof of principle. The lower level of accuracy has had a negative effect on a part of the research.

In addition to measuring low adhesion, the VIRM tribo trains can also measure: location, time, applied engine torque, axle load, wheel slip (yes/no), applied engine torque, train velocity and whether the magnetic track brake was activated. This measurement information can be used to make the desired relations. A major part of the measurement information derives from the diagnosis system already available on board of the train. As no complex measurement devices need to be installed it is possible to conduct measurements for a passenger train running in service. This also enables many measurements to be conducted. The measurement information is sent via GSM to a land computer, which executes the required analyses.

The 5 VIRM tribo trains conducted measurements in the period from January 30, 2008 through January 30, 2009. In order to examine the change of low adhesion in time on several locations it is necessary to conduct multiple measurements per day at a certain location. That is why the choice was made to deploy the measurement trains during the fall on a fixed route (Den Helder – Nijmegen).

Based on the measurement information, analyses were executed that led to the following insight:

- There is more low adhesion during the fall than there is beyond the fall, but beyond the fall low adhesion events with a low level of adhesion and/or over a long distance still occur.
- During the fall major differences from day to day occur.
- Low adhesion can occur over a length of tens of kilometres.
- There are locations (regions) where low adhesion occurs regularly; there are also locations (regions) where low adhesion rarely or never occurs.
- It has been observed that if low adhesion occurs at a certain location it usually occurs on the departing and arriving tracks.
- Extreme levels of low adhesion can occur very quickly (within an hour).
- It is plausible that low adhesion plays a major role in the fall dip for punctuality (driving on time).
- During the period when measurements were being conducted the braking system on the VIRM rolling stock proved almost adequate to prevent excessive braking distances due to low adhesion. For the VIRM rolling stock, low adhesion leads to a low safety risk.
- Approximately ¾ of driving time lost during the fall occurs during the first kilometre travelled on a route during acceleration and approx. ¼ occurred in the last kilometre on a route during braking.
- The driving time lost on a slippery route (< 10 km) due to low adhesion can amount to approximately 2 minutes.
- Drivers adjust their driving behaviour to slippery tracks both during braking as well as during acceleration and therefore influence the travel time (punctuality). Research into which measures should be taken to reduce the problems caused by low adhesion must include the driver's behaviour.

- The existing model for predicting low adhesion is only suited to send out an warning to drivers to be alert on low adhesion on a specific day. It is not good enough to warn drivers with a great level of reliability or to use the warning to take certain measures.
- Mainly for the traction control and to a less extent for the WSP (Wheel Slide Protection) there is room for improvement to optimally utilize the available adhesion. This could result in major improvements for the accelerating and braking performances on slippery tracks.
- The method developed to monitor performance can also be used for other subjects.
- Sandite does not work in such a way that after it has been applied low adhesion will not occur for the whole day. On approximately half of all days Sandite is applied without necessity.
- We have not been successful at obtaining insight into the effectiveness of the magnetic track brakes.

In the framework of this research method has been develloped which are able to obtain insight in the effectiveness of measures taken. Demonstrated is that the methods developed work by applying this method on the measures Sandite and magnetic track brake. To get a definitive insight in the effectiveness of these measures more measurements have to be carried out and a higher sample frequency of the VIRM tribotrain is required. Investigating the effectiveness of measures taken on low adhesion as occur in practise is very important. In that case it would be possible to make a cost – benefit analysis of measures and it would be possible to optimize the measures that are taken.

Based on a large number of the insights acquired it can be said that the method of the VIRM tribo trains combined with the chosen deployment and analysis methods are a powerful tool in gaining insight into the problem (performance monitoring).

The following recommendations/suggestions for improvement can be made based on the knowledge acquired.

- Determined is that low adhesion occurs at varying locations and times. From the point of view of costs and efficiency it is therefore desirable that measures to be taken must offer a large amount of flexibility. Measures that are taken in the train should be preferred over measures taken from the track for this reason.
- Test measures with the method developed. Based on the tested effectiveness of measures that were investigated a decision can be made whether or not to invest. The most obvious measures to take are: magnetic track brakes, sanders, improved traction control and Sandite.
- The prediction model can be improved by comparing the low adhesion that is predicted with the low adhesion that is recorded by the VIRM tribotrains; this will create a loop of feedback.
- The Sandite campaign can be improved by applying Sandite only on days that it really is necessary. Knowing when it really is necessary can be achieved based on the improved prediction model.

- The traction control and to a less extent the WSP have room for improvement. By better utilizing them the acceleration and braking performances on slippery track can strongly be improved.
- When ordering new rolling stock the following aspects must be taken into consideration:
    - How many driven axes and magnetic track brakes are required to offer the desired braking and acceleration performance?
    - The desire to install sanders on new rolling stock.
    - Which parameters must the diagnosis system measure and would it be wise to equip all trains with an on board – land – connection and so ensuring that all information available on board of the train is also available on land?
- Investigate why drivers adjust their driving behaviour during acceleration. If the investigated driving behaviour deviates from what the optimal acceleration performance offers it is advisable to teach drivers a new driving behaviour.
- Use the method developed to determine the braking distance and braking distance distribution for all train types available in The Netherlands. This information is very important to determine the optimal (yet still safe) utilization of the track.

The low adhesion problem is a complex problem influenced by many factors. In this thesis, the factors and the relationships between the factors are described and made measurable.

In summary it can be concluded that thanks to this research the problem can be clearly measured. The observations are based on objective measurements instead of on subjective observations. This research has shown how the low adhesion problem occurs in practice; the problem has been made comprehensible. Based on this insight/understanding a large number of suggestions for improvement have been able to be formulated. Also, performance monitoring can determine whether the problem dimishes after measures have been taken.

Contents

1 AdRem's research program

The problem of slippery tracks is inherent to the applied method of accelerating and decelerating a train by wheels of steel on steel tracks. The advantage of a low rolling resistance is accompanied by the disadvantage that the forces, which are transmitted by the wheel to the rail, needed for traction and braking are limited. If the wheels have to deliver a higher force to the rail than they can transmit, the wheels start to slip. Slipping is possible in both acceleration and deceleration. For at least 150 years now, research has been conducted on how to improve this force transmission of power. This has resulted in over one million scientific publications on this subject (reference [1]).An example of a locomotive equipped with a sandbox to improve the friction between wheel and rail is displayed in figure 1.1.

The need for faster, more efficient and safer transportation over the past decade, has made it increasingly important to improve the transmission of force. As a result thereof, NS (biggest train operating company in the Netherlands) and ProRail (Dutch infrastructure manager) have initiated the low adhesion research program AdRem (Adhesion Remedy).

Figure 1.1 Sanders on an old locomotive.

1.1 AdRem's goals

The goal for this research program is twofold:

1. Obtain a better insight into the problem.
2. Give solutions to reduce the problem.

1.2 Research philosophy

A brief search through literature results in a large number of documents that cohere with this subject. These documents show that the problem of slippery rails covers a wide knowledge area (see reference [1] and [2]). This includes: material technology, organic chemistry, rolling stock technology (also braking techniques, control techniques, traction installation), transportation processes, driver behaviour, safety, infrastructure, signaling system, timetable, tribology, dynamic behaviour of the train, weather, measuring technique, etc. The problem has been researches from each of these knowledge fields. This has not resulted in an acceptable reduction of the problem.

The idea behind AdRem is, to no longer view the research from one angle but from various angles, a multi-disciplinary approach. By viewing the problem as a whole it might be possible to find a solution that will lead to a reduction of the problem caused by slippery track (low adhesion).

1.3 Knowledge areas

As AdRem's budget was not unlimited it was necessary to make a choice for certain knowledge areas. This is a difficult choice because upfront it is not completely clear which knowledge areas are important in achieving the desired insights. The following knowledge areas were chosen:

- Plant physiology (University of Wageningen).
- Tribology (University of Twente chair in tribology).
- Dynamic behaviour (Delft University).
- Design technique (University of Twente department design, construction and management).

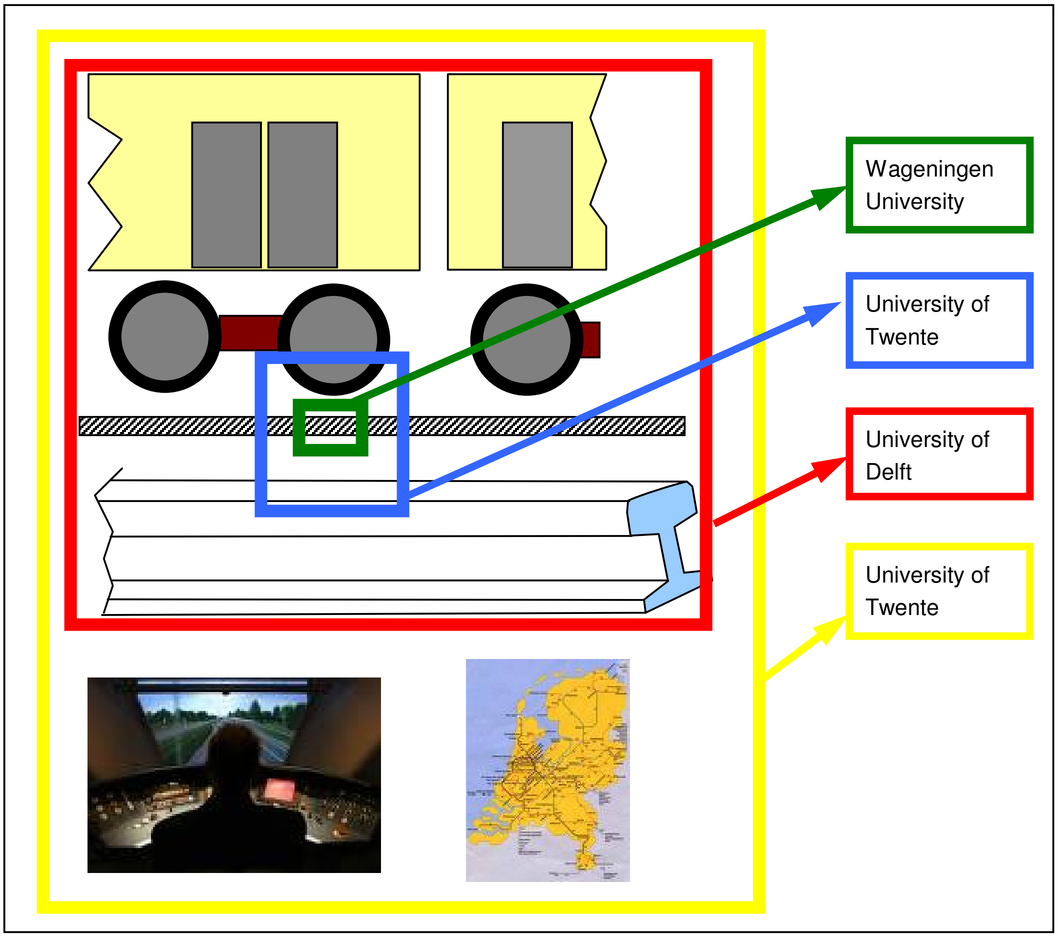


Figure 1.2 Scope of the research of the four AdRem researchers.

After an initial period, the researchers distributed the work amongst each other. University of Wageningen focused on the research of which substances (intermediate layers) can be found on the Dutch tracks (in green frame figure 1.2). The chair Tribology at the University of Twente focused on researching the wheel-intermediate layer-rail interaction (blue frame in figure 1.2). The University of Delft researched the train's movement on the rails (red frame in figure 1.2). Finally, the department Design, Production and Management (DPM) of University of Twente researched how the train performs in relation to its surroundings (performance monitoring). This is displayed in the yellow frame in figure 1.2. For instance, the Dutch railroad network and the behaviour of the driver. This thesis was written within the framework of that assignment.

1.4 Organisational structure

AdRem's organisational structure is displayed in figure 1.3. The project group is carrying out the research. The project group consists of project management, four researchers and technical support. Project management consists of two project leaders, one from NS and one from ProRail. The project leaders manage the day-to-day process and offer their feedback to the control committee. The researchers conduct the research (see §1.3). An employee from Delta Rail and one from Lloyd's Register offer technical support. Both employees assist the researchers and project management.

Project management, project management's supervisors and the researchers' coaches take part in the control committee. The control committee's task is to ensure that NS and ProRail get a useful research. Also, the control committee decides on research proposals that require extra investment.

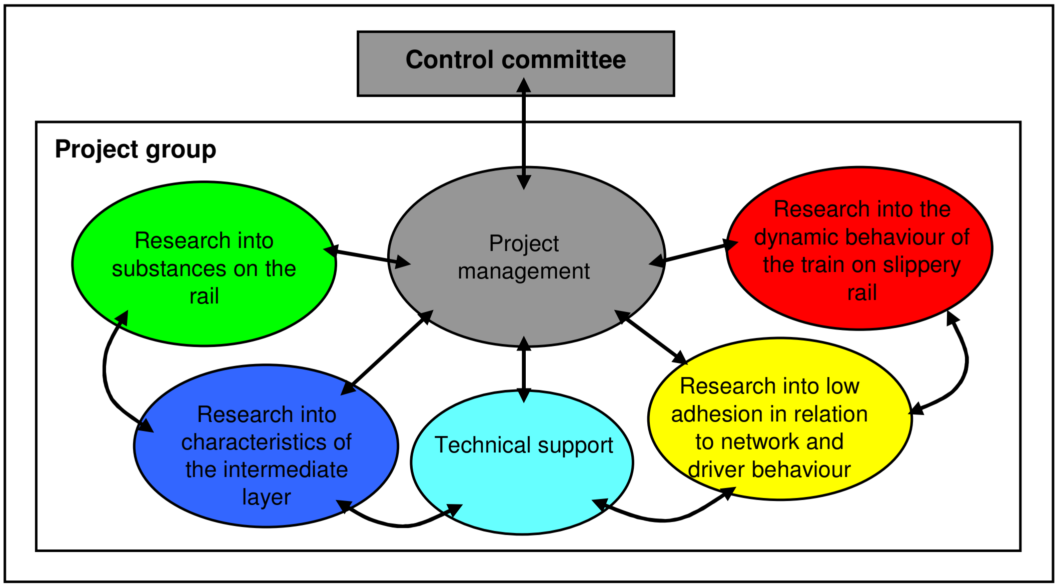


Figure 1.3 Organisational structure research program AdRem.

2 Introduction

In this chapter the problem of low adhesion will be analysed in general. The insight will offer answers as why the problem has not been solved yet and which knowledge is still missing.

This chapter is compiled as follows: In §2.1 the causes for low adhesion will be presented. Subsequently in §2.2, the effects of low adhesion (slipperiness) on train traffic will be stated. Then in §2.3 the measures that already are in place will be listed. §2.4 describes the research strategy with the research questions. This includes how the answers to the question contribute to the development of effective and efficient measures. Then in §2.5 the research questions that AdRem must answer are summarized. Also this paragraph lists which research questions should be raised in view of this assignment.

2.1 Causes of low adhesion

The advantage of using steel wheels on steel rail is its low rolling resistance. This advantage, however, also poses a disadvantage: the wheel can only transmit relatively limited braking and traction forces to the rail. If the wheels have to deliver a higher force to the rail than they can transmit, the wheels start to slip. The system is developed such that the desired forces can be transmitted in most conditions. Pollution of the rail often in combination with moisture can lead to the fact that the desired braking and traction forces cannot be transmitted. The most common causes for low adhesion are (see reference [2] and [3]):

- Accumulated leaves (see figure 2.2 and 2.3) in combination with moisture.
- Rust in combination with moisture (see figure 6.1).
- Feces, toilet paper and paper handkerchiefs from the train's toilet that discharges onto the track (see figure 2.4).
- Air pollution that precipitates onto the track.
- Lubricants applied to reduce friction in curves (see figure 2.5).

It is reported that co-researchers at AdRem are conducting further research into the substances causing low adhesion on the Dutch track. What is on the track is important in order to choose the most appropriate solution. In addition to low adhesion due to substances (intermediate layer) on the track it has been determined that the following circumstances also lead to extra susceptibility to low adhesion (see reference [4]):

- Low axle load.
- Infrequently used track.
- Trains that only use disc brakes for braking.
- Routes where only one type of train runs.
- Routes where no freight trains run.
- Track sections with a narrow course.
- Short trains.

Figure 2.2 Leaves on the rail.

Figure 2.3 Leaves on the wheel.

Figure 2.4 Feces on the track.

Figure 2.5 Lubricants on the rail.

2.2 Consequences of low adhesion

It is important to have good insight into the consequences because they indicate how urgent it is to find a solution for the problem, which investment to reduce the problem is reasonable and which costs could be saved. Major consequences of low adhesion are:

- Decreased safety (red-signal passages and collisions).
- Reduction of track capacity.
- Extended travel time and disruption of driving on time.
- Damage to equipment and infrastructure.
- Image damage.

Safety, rail capacity and driving on time influence each other. Optimizing one will have an influence on the other two. Safety can be increased by increasing the distance between trains (increasing distances between signals). This however would have a negative effect on the track capacity. Considering the fact that the Dutch railroads are so busy unnecessary safety margins cannot be permitted. Driving on time can be improved by allowing extended margins in travel time. This also will lead to a reduced track capacity. In the following paragraphs these subjects will be discussed in more detail. Finally a few minor consequences will be mentioned.

2.2.1 Influence of low adhesion on safety

Signal distances are determined by the braking performance of the train with the worst braking performance, which is admitted on the railway. This stipulation has a margin for unforeseen circumstances. One of those unforeseen circumstances is low adhesion. This margin, however, is not so large that it can prevent red-signal passages and/or collisions due to extreme low adhesion. Luckily extreme low adhesion is rare. The driver must compensate for this 'hole' in the security systems. He must recognize slippery track and subsequently react adequately; brake earlier. Driving experience is required in order to be able to judge whether it is slippery.

The safety situation described above therefore depends on the qualities of the driver. This is not an advisable situation. Nor does it comply to the safety philosophy behind (parts of) the braking system. This philosophy entails that the braking and operating system's safety is guaranteed by: 1. Subsystems give a signal when they fail, 2. Make subsystems redundant or 3. Make subsystems fail-safe. These philosophies prevent that a singular failure in the system can lead to an accident. Braking on a slippery track does not meet these requirements. After all, a system that takes over if the driver performs the wrong handling in case of low adhesion does not exist.

It should be noted that if, in the far future, trains will be running without driver there will not be an driver to detect that it is slippery and who can act adequately if he notices slippery circumstances. In this case, preventing peaks in the braking distance due to low adhesion is even more important.

Effects of low adhesion on safety
From January 1999 through January 2006 low adhesion in combination with the wrong interpretation of circumstances by the driver resulted in 128 red-signal-passages. During the same period, a total of 2192 red-signal-passages occurred due to circumstances other than low adhesion. This information was supplied by the Inspection for Transport and Public Works (IVW). It is not possible to refer to a reference because it concerns confidential information.

Given the fact that all trains combined stop 1 billion times a year, 128 red-signal-passages in 7 years due to low adhesion is a relatively low number. The number of stops per year is estimated based on the 48.000.000 kilometers that is traveled each day (data NS) and an estimate of the average distance of 16 km between 2 stations where the trains stop.

Facts regarding red-signal passages due to low adhesion.
30% of the red-signal-passages occurred during the second half of October, 15% in the first half of November and 11% in the second half of November. 56% of all cases occur during the fall. The length by which a train passes a signal is usually a few meters, but in a few cases it is hundreds of meters. Of the 128 red-signal-passages due to low adhesion 40 passed the red signal with 25 meters or more. Of those, 7 occurred in other seasons than the fall. Relatively fewer red-signal-passages occur with modern rolling stock than with older equipment. This information is also coming from the Inspection for Transport and Public Works (IVW).

Conclusion
Based on these numbers the conclusion can be drawn that in approximately 5% of the instances low adhesion plays a part in the red-signal-passages.

2.2.2 Influence of low adhesion on the rail capacity

In view of the acute lack of the Netherlands track capacity ProRail is presently investigating whether it is possible to increase track capacity. Reference [30] shows that making more efficient use of the track is less expensive than building new track. Therefore, research is being conducted into whether it is possible to reduce the distance between two successive signals (signal distance) so that trains can run closer to each other resulting in an increased track capacity but also in a reduced safety margin. Reducing the signal distance is possible because the braking performance of modern rolling stock has improved.

It is expected that in the future the switch to the ERTMS security system will be made. When ERTMS is implemented the signal distances will depend on the train's braking performance. This will lead to increased track capacity. But it will also mean that trains with a better braking performance than the trains with the least braking performance will run closer to each other. As a result, a certain safety margin will be lost.

With regards to safety the Dutch railways have a standstill principle. This means that rail transport is not allowed to become less safe than it was in the past. The inspection for Transport and Public Works therefore wants to see proof that by reducing the distance between signals the safety does not decrease. This information is presently not available. Should, due to reducing the distance between signals or implementation of ERTMS safety not be on an acceptable level, additional measures will have to be taken.

Conclusion

Due to the fact that building new track is extremely expensive, it is expected that the benefits of track capacity improvement by reducing the signal distances and implementation of ERTMS will be high. It will be necessary to ensure that safety level remain the same. In order to make a proper choice between track capacity and safety it is important that a proper risk assessment is made to ensure that unacceptable safety risks are not taken. Due to the fact that it cannot be determined where and when, what level of adhesion occurs, it is not clear how large this risk is and it is therefore impossible to make the required risk analysis.

2.2.3 Travel time increase and disruption of driving on time

Travel time can increase as a result of low adhesion during acceleration and braking. This results in a longer travel time, see figure 2.6.

Figure 2.6 Notice board in entrance hall of a station with text: "Coming days low adhesion due to leaves: Take into account a longer travel".

Waste of travel time during acceleration part of the ride
As a result of the fact that a train cannot transmit the traction force, applied by the driver, to the rail the train will not be able to reach the acceleration required to achieve the desired travel time. It is not clear how much time is wasted as a result of low adhesion.

Waste of travel time during braking part of the ride
Waste of travel time during the braking part of the ride occurs because the driver assumes that the rails are slippery. Formally an driver is not responsible for red-signal-passage caused by low adhesion. But because an driver cannot prove the cause of a red-sign-passage or collision he generally is held responsible. Drivers feel this is very unjust. The procedures that an driver has to go through after a red-signal-passage or collision have a lot of impact on the driver. Moreover, a collision or red-signal-passage is a blemish on the driver's professional honor. Therefore the driver has a lot to gain by preventing a collision or red-signal-passage.

If a driver has the impression that it could be slippery he will brake more carefully, which will have a consequence on travel time and punctuality. Because estimating low adhesion is a subjective observation by the driver and because incorrect estimation has large consequences, the driver will likely always wrongly brake carefully. It is not clear how much time is wasted as a result of a driver braking carefully. The basic problem is that an driver has to meet contradictory requirements: driving safely and being on time.

Decrease of driving on time in the fall

The NS driving on time data (see table 2.1) shows that in November of 2006, 2007 and 2008 driving on time percentage was respectively 11.2, 7.0 and 8.5% lower than average of that year. This information is coming from NS intranet. A lower level of punctuality is also evident in October and December. The total dip in driving on time percentage in the fall leads to a decrease of approximately 1% on annual driving on time percentage. Within the railways this dip is attributed to low adhesion. Reference [5] indicates that improving driving on time percentage by 1% will lead to a profit of € 2.500.000 for the NS.

	2006		2007		2008	
	Monthly average driving on time percentage	Difference compared to average	Monthly average driving on time percentage	Difference compared to average	Monthly average driving on time percentage	Difference compared to average
January	85,8	+1,0	85,9	-1,5	88,3	+1,5
February	88,3	+3,5	86,1	-0,9	88,4	+1,6
March	85,3	+0,5	88,4	+1,4	87,5	+0,7
April	90,4	+5,6	87,1	+0,1	88,7	+1,9
May	87,8	+3,0	88,3	+1,3	87,3	+0,5
June	86,5	+1,7	88,0	+1,0	87,8	+1,0
July	83,3	-1,5	89,1	+2,1	89,3	+2,5
August	88,9	+4,1	91,2	+3,2	90,6	+3,8
September	84,4	-0,4	87,8	+0,8	87,8	+1,0
October	80,7	-3,1	86,4	-0,6	81,9	-4,9
November	73,6	-11,2	80,0	-7,0	78,3	-8,5
December	82,7	-2,1	86,0	-1,0	85,2	-1,6
Annual average	**84,8**		**87,0**		**86,8**	

Tabel 2.1 Average monthly driving on time percentage in 2006, 2007 and 2008.

Disadvantages for travelers

In the Ministry for Housing, Spatial Planning and the Environment's memo on mobility, public transport reliability (reference [38]) is considered very important. That the government feels strongly about reliability is evident due to the fact that driving on time forms part of the transport concessions for train operating companies. The memo states that for the railways the goal is to achieve 89-91 % of the trains running on time in the period 2011-2020. A quick scan (see reference [6]) by the CPB has calculated the advantage of driving on time for travelers. According to the CPB, the profit for travelers as result of 1% improvement of driving on time is € 6 – 8 million.

Conclusions

This paragraph shows that a reduction of the driving on time dip in the fall can be very profitable. It needs to be further investigated by NS and/or Prorail how large the profit exactly is. It is unclear to what extent the dip is caused by careful braking by the driver or by problems with acceleration. In order to be able to take effective measures insight into theses issues must be gained. If the driving on time dip occurs as a result of careful braking by the driver when he thinks it is slippery, than it is necessary to:

- Develop a system that can warn the driver for low adhesion so that he no longer needs to brake carefully without reason.
- Make sure that peaks in the braking distance are prevented by making changes to train or infrastructure (see §2.3).

Remark

If in the future certain routes are serviced without a timetable it is possible that driving on time will become a less important factor.

2.2.4 Damage to equipment and infrastructure

Damage to the track

Most damage to the track as a result of low adhesion concerns Squads (see figure 2.8). Squads occur as a result of wheels slipping on the track during acceleration while the train stays standing still. According to ProRail's reference [6] it is unclear whether this leads to significant expenses.

Figure 2.7 Squad on the rail.

Damage to the wheels

Wheels can block (stand still in comparison to the rails) when braking on a slippery track resulting in a flat area on the wheel, which is referred to as a flat (see figure 2.8). In 2001 NedTrain Consulting (see reference [7]) conducted research into the number of flats that were caused in the various types of rolling stock. They also investigated which costs were involved. In addition to the cost for restructuring the wheel, the following costs were included: transportation of the train to the workshop, the unavailability of the train and the fact that restructuring decreases the life span of the wheel set. The mentioned reference shows that in 2001 restructuring itself cost approx. €400,- per set of wheels. The other costs turned out to be quadruple. That brings the average cost per restructuring of a wheel set to approximately €2500,-.

Measuring systems (Gotcha) are installed in the track, which can determine whether a train has a flat. Based on Gotcha it turns out that in the VIRM series approximately 150 flats occur each year. The damage to the VIRM fleet therefore amounts to approximately €375.000. As the VIRM fleet accounts for a third of the total number of axles, the annual damage for repairing flats is estimated at €1,1 million.

Conclusion

Preventing wheels from blocking can result in substantial cost savings.

Figure 2.8 Flat on the wheel.

2.2.5 Image damage

In the fall of 2002 many trains were cancelled and ultimately the train service was discontinued all together due to low adhesion. This was a huge disgrace for the railways and seriously damaged the NS and ProRail's image. Figure 2.9 illustrates this. It is unclear how much the damage was expressed in money.

Figure 2.9 Silly cartoons contribute to a bad image.

2.2.6 Other consequences

A meeting with stakeholders of NS and ProRail was held in order to determine whether all the consequences for the railways related to low adhesion, were known. Reference [8] shows the results of that meeting. Other consequences as a result of low adhesion surfaced during this meeting, but the damage they cause is limited compared to the damage caused by the consequences mentioned in this paragraph.

2.2.7 Conclusion

Preventing the damage mentioned in this paragraph can lead to substantial costs savings for NS and ProRail. To end this certain measures will need to be taken. The most important damages are: decreased driving on time percentage, reduced track capacity, reduced safety and flat repairs.

2.3 Measures

Low adhesion has caused problems for train traffic for over a century. The fact that since then many trains have been equipped with sanders illustrates this (see figure 1.1). The problem of low adhesion can be solved by for instance a rack railway (see figure 2.10), a maglev train (see figure 2.11) or by installing rubber wheels like in the subway in Paris (see figure 2.12). The assumption is that the benefits of these measures will not outweigh the costs therefore they are not included in the scope of this assignment.

Figure 2.10 Rack railway.

Figure 2.11 Maglev train.

Figure 2.12 Subway train in Paris equipped with rubber tyres.

2.3.1 Existing measures

A large number of measures, divided into 7 categories, is listed below.

1. Measures to apply the required roughness to the wheels/the track:
    - Applying rough material (sanders (figure 2.13 and 2.14), Sandite (figure 7.18 and 7.19), friction modifier.
    - Roughing up the track/wheels (magnetic track brake (see figure 7.20 and 7.21), brushing the track, lasering the track (see figure 2.15), making wheel to slip in order to wear off the intermediate layer.
    - Roughing up the wheels (brake block).
    - Cleaning the track (water jetting (see figure 2.16) removing alge, dissolving the intermediate layer).
2. Measures to prevent low adhesion:
    - Prevent leaves on the track (leaf guards (see figure 2.18), fences to prevent leaves from blowing onto the track, preventive pruning policy, vacuuming the leaves (see figure 2.17), aerodynamic adjustments to the train.
    - Reducing rail oxidation (stainless steel rails).
3. Applying more braking power (magnetic track brake, eddy current brake).
4. Optimizing transmission of the present braking/traction power (WSP, traction control).

5. Preventing damage to wheels / track (WSP, traction control).

6. Warning drivers:

- Organizational measures (special fall timetable).

Figure 2.13 Sander.

Figure 2.14 Nozzle of the sander.

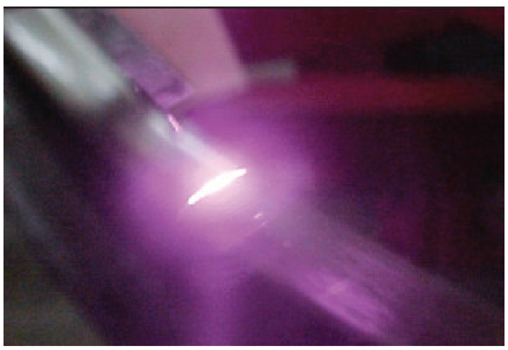


Figure 2.15 Lasering the track

Figure 2.16 Water jetting; cleaning the track (England).

Figure 2.17 Vacuum cleaner for leaves (France).

Figure 2.18 Leaf guards on the track to prevent leaves on the track.

It is noted that more measures can be found in literature and in patents literature. The following of the measures mentioned above are used in The Netherlands: sanders, Sandite, magnetic track brake, preventive pruning, use of modern WSP and traction control and warnings for low adhesion.

Grouping of the measures

In view of this research it is important to make a further division of the measures. Measures that depend on the location and measures that depend on the situation. Both are further explained below.

Location-dependent measures

This type of measure is taken on a certain location because it might be slippery there. Determining the location can take place based on prediction of low adhesion, detected low adhesion or past experiences. Examples of measures depending on the location are: Sandite, water jetting, preventive pruning. Warning drivers for low adhesion at a certain location can also be considered as a measure that depends on the location.

Situation-dependent measures

This type of measure is taken in the train where low adhesion has been detected. Based on this observation measures are taken. Examples of this are: WSP/traction control and sanders. A magnetic track brake that is only applied during low adhesion can also be considered as such a measure. Measures depending on the situation are actually measures that ensure that a train's braking system is sufficiently equipped to brake under all low adhesion circumstances.

Conclusion

This paragraph shows that many measures have already been developed, but that it is not clear how effective the measures are.

2.3.2 Problems with measures taken

Lack of insight into effectiveness

If so many measures have been developed, then why does the problem still exist; why is there a driving on time dip in the fall and why do trains still pass red signals in case of low adhesion?

The reason for this is that at present it is not clear how effective the measures taken, are in the day-to-day practice. This is because at present a measuring tool that offers that knowledge is not available. Because it is difficult to determine the effect of the measures in practice, it is hardly possible to improve them; also there is no feedback that gives insight that it is a positive improvement.

Lack of insight on locations and moments that low adhesion occurs

Choosing the most effective measure is difficult because in The Netherlands it is not clear where and when it is slippery and to what extent. At present the knowledge about where and when it is slippery is mainly based on the drivers' experience.

Lack of insight into the causes of the driving on time dip

In § 2.2.3 it was mentioned that the driving on time dip in the fall can occur due to problems with acceleration or by the driver's braking behaviour. These facts are important when measures need to be taken. If the driving on time dip is caused by the driver's braking behaviour it is important that the driver can trust the prediction for low adhesion or the braking system (no more peaks in the breaking distance possible). If this trust is missing the driver will continue to brake carefully and any measure or prediction will be pointless.

2.3.3 Assessing effectiveness of measures

The existing measures such as sanders, Sandite and magnetic track brakes appear to be obvious measures expected to solve the problem. Nevertheless the problem of low adhesion still exists. Do these measures not work as expected or do they in fact work and would the problem of low adhesion be much worse if these measures were not taken?

Insight into these questions is lacking because the effectiveness of the measures is not determined. The reason is that a measuring tool that is capable of measuring the extent of the low adhesion before and after a measure has been applied is not available. So far, the effectiveness of measures is assessed in lab research or by testing rails that have artificially been made slippery. Below both tests are further explained in combination with their most important shortcomings. Further information can be found in reference [14].

Assessing effectiveness by lab research
Lab research to test the effectiveness of a measure is mostly conducted on a two-disc machine (see figure 2.19). One disc represents the rails and the other disc represents the train's wheel. Most two-disc machines allow for adjustable contact pressure between both wheels. By applying a slippery substance such as leaves, grease and paper tape, often in combination with moisture, slippery conditions can be achieved. Subsequently an accelerating torque is applied to one disc and a braking torque is applied to the other. By measuring the tangential force in the contact surface and the slip between both wheels it is possible to gain insight into the adhesion between both wheels (discs). By applying a measure on the slippery wheels, it is possible to get insight in the effectiveness of the applied measure. The most important shortcoming of this method is that it is difficult to create the same circumstances, which prevail in practice.

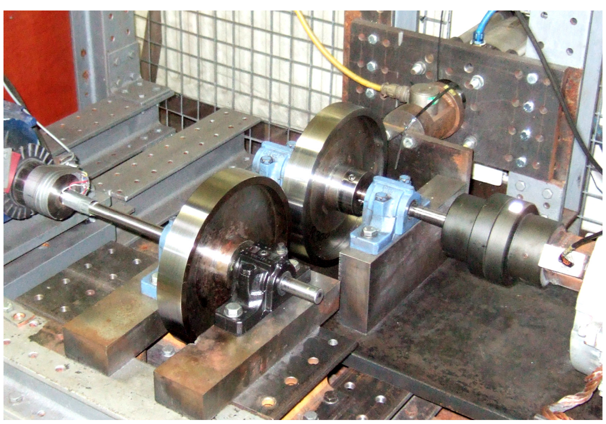


Figure 2.19 Two disc machine (lab arrangement).

Assessing effectiveness of track which has artificially been made slippery
Assessing low adhesion in practice is done by artificially making the track slippery with for instance leaves, grease and paper tape, sometimes in combination with moisture. A hand tribometer (see figure 4.2) is used to measure the roughness of the track. Subsequently a brake process is performed on the artificially slippery track; the reference measurement. The braking distance (and/or deceleration) is determined. Again the track roughness is determined by using the hand tribometer.

After this, the measure is applied (for instance Sandite) or the measure in the train is activated (for instance sanders) and again a brake is conducted after which the braking distance is determined; the test measurement. The reference measurement and test measurement braking distances are compared. The difference is indicative for the effectiveness of the measure. Of course, these tests can also be conducted by determining the effectiveness of measures during acceleration. The aforementioned test methods to assess measures have a number of shortcomings:

1. The hand tribometer only offers a general insight into the extent of adhesion making it impossible to determine with precision whether the low adhesion prior to both braking processes was equal.
2. The extent of adhesion is strongly influenced by circumstantial conditions (for instance radiant heat or dampness) making it difficult to maintain consistent testing conditions during both the reference as well as the test brake.
3. It is unclear whether the test medium is comparable with low adhesion as it occurs in practice.
4. The test method is labour-intensive because it takes a lot of time to create the right conditions on the rails.
5. Only a limited amount of tests can be conducted because after the first reference and test brake, the rails need to be cleared of the measure and must be made artificially slippery all over again.

2.4 Low adhesion problem summarized

Figure 2.20 displays a summary of the situation of the low adhesion problem. In the initial situation it is only scarcely clear what occurs in practice with regards to low adhesion. Basic knowledge on low adhesion is hardly available: where and when is it slippery and to what extent, which deceleration/acceleration performance can a train accomplish on low adhesion, how often does low adhesion occur, how does the driver operate the train during low adhesion conditions, what are the consequences of low adhesion on driving on time, safety and track capacity. The knowledge that is available is for the most part based on the subjective observations made mainly by drivers.

In order to improve performance on low adhesion certain actions/measures are taken. But it is not or only limitedly known how effective these measures are in practice. This makes it difficult/impossible to make a cost-benefit analysis. Therefore it is difficult to answer the question: does it make sense to invest in measures? It is also difficult / impossible to optimize existing measures.

By taking measures a new situation is created. It cannot yet be determined whether the situation has improved compared to the initial situation. In fact, it cannot be determined whether the problem is solved / reduced. Because there is no feedback from the system it is difficult to purposefully approach the problem.

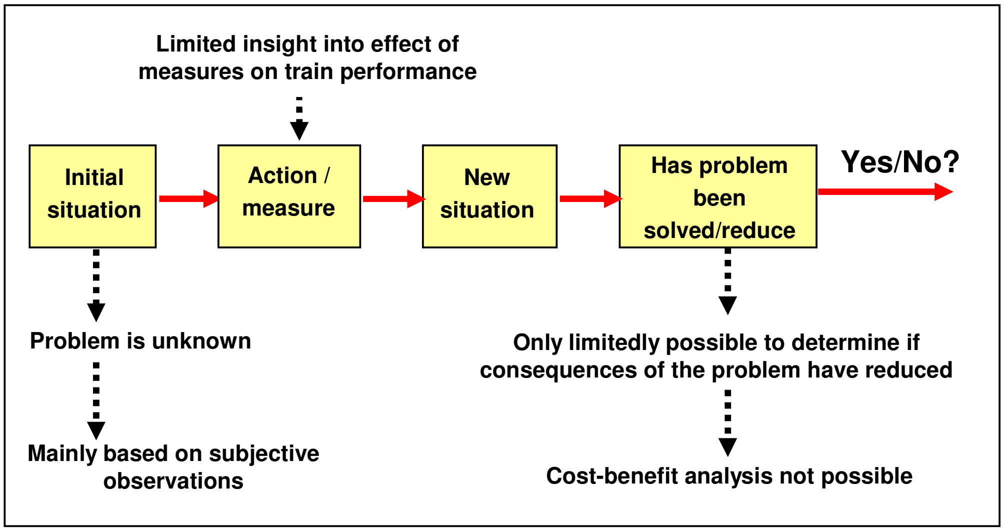


Figure 2.20 General presentation of the low adhesion problem.

2.5 Defining AdRem's research questions

NS and ProRail initiated the research project AdRem because they experience the inconvenience caused by low adhesion. In §2.2 it is reported that this inconvenience in fact leads to substantial costs. This paragraph lists and substantiates the research questions. The answers to the research questions should contribute to measures that will help limit the inconvenience.

2.5.1 Reducing the consequences of low adhesion conditions

In order to reduce the consequences of low adhesion it is necessary to take measures. To achieve effective and efficient measures a strategy has been prepared. This strategy is displayed below and starts with the most elegant solution and ends with the least elegant solution. In these solutions some knowledge is missing. For each solution it has been indicated which questions remain unanswered. The solution strategy, which has been divided into 6 mainstream solutions, is outlined below.

1. Solving the problem at its core

The low adhesion problem is, as mentioned earlier, caused by the fact that a steel wheel can only transfer limited tangential forces to a steel rail. The most elegant way to solve the low adhesion problem is to choose for an alternative method to transmit the braking and acceleration forces. For example: a rack railway, a maglev train or by applying rubber wheels (see figures 2.10, 2.11 and 2.12). Considering the high investment costs this solution mainstream is not further considered. For the following solutions the existing steel wheels and the existing steel rail will continue to be part of the system.

2. Measures to prevent the rail from becoming slippery

Another solution is to prevent the rail from becoming slippery. For this, it is necessary to know which substance is on the rails and where that occurs so that measures can be taken to prevent that substance from ending up on the rails. This leads to the first research question:

Research question 1:
What is where on the track?

As previously indicated in §2.1 a large number of factors can lead to slippery conditions. It is expected that it will prove to be almost impossible to prevent all of these causes at all times.

3. Technical measures that guarantee minimum braking and acceleration performance
If it is not possible to prevent it from becoming slippery at all times, an elegant solution would be to take measures that ensure that the required performance can be accomplished on slippery track. To develop and deploy such measures it is necessary to get a better insight into the problem.

<u>Insight into the problem</u>
§2.2.1 indicates that red-signal-passages and collisions occur due to slippery conditions. In order to be able to improve this situation it must become clear what the performance of the present braking system is under slippery conditions. This leads to research question 2:

Research question 2:
How does the present braking sytem perform?

As previously indicated the driver tends to brake carefully (earlier) in case of possible slippery conditions. This has an effect on the travel time. Another cause that could lead to travel time loss is that the wheels cannot transmit the required acceleration forces to the rail. A driver can add to the loss in travel time if he/she reduces engine torque in case the train slips. This leads to the situation that the wheels that do have enough grip also transmit less force than required. This leads to research question 3:

Research question 3:
Is the driving on time dip in the fall caused by low adhesion. If yes, is this dip caused by acceleration or braking. And what is the influence of driver's behaviour on acceleration and braking performance.

<u>Measures</u>
To achieve a situation where there is a guaranteed maximum braking distance, there are two general possibilities the location-dependent and situation-dependent measures (see §2.3.1). For the location-dependent measures it is necessary to know where and when it is slippery so that the required measures can be taken on location. This leads to research question 4:

Research question 4:
Where and when is it slippery? To what extent?

At present a system that can determine with sufficient precision (measure or predict) where and when it will be slippery so that measures can be taken on location is not available. A combination of measuring/predicting and measures must lead to a guaranteed pre-determined minimum level of adhesion. Only if a determined maximum braking distance has been guaranteed can a driver trust that fact and need he/she not brake carefully (earlier) due to (possible) low adhesion conditions.

However, it is possible that this method is not an option. If low adhesion conditions can occur rapidly and/or constantly in different locations that will complicate measurability/predictability, possibly even make it impossible to measure/predict. In that case measures cannot be taken on time and therefore a minimum level of adhesion will not always be able to be guaranteed. This leads to research question 5:

Research question 5:
How fast can low adhesion occur and to which extent does low adhesion occur in various locations?

To determine what the most effective measures are, it is essential that it is clear which substance (see research question 1) is on the rails and at which location that occurs and where and when it is slippery (research question 4). But also, it is necessary to know what the characteristics of the various intermediate layers are. Based on the characteristics of the interlayer it can be determined which measure is best to combat low adhesion. This leads to the following research question:

Research question 6:
What are the characteristics of the various kinds of slippery intermediate layers?

For this solution it is important that the measure taken are effective as such that it can guarantee a certain maximum braking distance. §2.3 shows that the effectiveness of the existing measures is only very limitedly clear. This leads to research question 6:

Research question 7:
What is the effectiveness of present measures? Is it possible to guarantee a minimum braking distance with the present measures?

4. Warning drivers
If is turns out that it is not possible to develop a technical measure that will guarantee a minimum braking distance, a possible solution could be warning the drivers for low adhesion conditions. If drivers can trust the warning, that will increase safety. In addition, it will help improve driving on time. At present, a driver probably brakes carefully because he wrongly assumes it could be slippery. Warning him will prevent him from wrongly braking carefully, which will have a positive effect on driving on time percentage.

It is imperative to ensure that a situation where a driver reaches slippery track without having received prior warning does not occur. However, it is not certain whether it is possible to measure or predict sufficiently in order to warn drivers adequately. Research question 6 applies to this solution mainstream.

5. Technical measures that improve minimum braking and acceleration performance but do not guarantee improvement under all conditions
If the following 2 conditions are met: 1. If the level of safety is acceptable and 2. If driving on time is not or barely influenced due to careful braking by the driver when he assumes it is slippery.

In that case it will not be necessary that a maximum braking distance is guaranteed. Also, although it might be advisable to guarantee a maximum braking distance, it might not be possible to realize it in practice. In order to be able to develop solution mainstream 5 it is necessary to have knowledge on the effectiveness of the measures (research question 5) and knowledge on where and when it is slippery (research question 3).

6. Organizational measures
If technical measures do not result in a successful solution it will need to be investigated whether organizational measures could offer a solution. This could be for instance a special fall schedule with an extended travel time per route. The choice was made to eliminate solution mainstream 6 from the scope of AdRem’s research.

2.5.2 A better understanding of the problem

In §2.4 a number of research questions are listed regarding successful implementation of measures. These questions relate to AdRem's goal to develop measures. AdRem had a second goal: a better understanding of the problem. Research question 7 is based on this goal:

> Research question 8:
> *A better understanding of the low adhesion problem*

2.5.3 Summary of AdRem's research questions

Table 2.2 lists the various research questions in the rows. The columns show to which research the questions belong.

	Research questions	**WUR**	**UT**	**TUD**	**UT CTW**
1	*What is where on the track?*	[green]			
2	*How does the present braking system perform?*				[yellow]
3	*Is the driving on time dip in the fall caused by low adhesion? If yes, is this dip caused by acceleration or braking? And what is the influence of drivers' behaviour on acceleration and braking performance?*				[yellow]
4	*Where and when is it slippery? To what extent?*	[green]	[blue]		[yellow]
5	*How fast can low adhesion occur and to which extent does low adhesion occur in various locations?*				[yellow]
6	*What are the characteristics of the various kinds of slippery intermediate layers?*		[blue]		
7	*What is the effectiveness of present measures? Is it possible to guarantee a minimum braking distance using the present measures?*			[red]	[yellow]
8	*A better understanding of the low adhesion problem?*	[green]	[blue]	[red]	[yellow]

Table 2.2 AdRem's research questions.

2.6 Research questions to be answered in view of this assignment

The research questions onto which this assignment attempts to shed light have been marked in yellow in table 2.2: they are questions 2, 3, 4, 5, 7 and 8. Question 8 is a very basic question that is not specifically researched in depth. By answering the other questions, this question will automatically be answered.

In order to answer questions 2, 3, 4, 5 and 7 it is necessary to have disposal of a measuring tool. As mentioned in this chapter there presently is not a measuring tool available that can offer insight. In order to be able to answer the research questions for this assignment an appropriate measuring tool will need to be developed. The final research questions for this assignment are:

1. Develop a measuring tool that can offer insight into the following research questions?
2. What is the present braking system's performance under low adhesion conditions?
3. Is the driving on time dip in the fall caused by low adhesion? If yes, is this dip caused by acceleration or braking? And what is the influence of drivers behaviour on acceleration and braking performance?
4. Where and when is it slippery? To what extent?
5. How fast can low adhesion occur and to which extent does low adhesion occur in various locations? In other words: how predictable / measurable is low adhesion?
6. What is the effectiveness of present measures? Is it possible to guarantee a minimum braking distance using the present measures?

3 Problems measuring low adhesion

Chapter 2 shows that it is imperative to develop a measuring tool. This chapter describes the theoretical knowledge proving the difficulty involved with measuring low adhesion.

3.1 Theory on low adhesion

In order to be able to compare the adhesion[1] of one part of the track to that of another part when a train wheel passes, it is imperative to have a standard for that adhesion. That standard must offer insight into the maximum tangential force that the wheels can transmit to a certain part of the track.

If a train wheel transfers a certain tangential (acceleration of braking) force T to the rail there has to be a certain minimum adhesion in order to prevent the wheel from slipping. In other words, in case of a certain adhesion in the wheel/rail contact the wheel can transfer no more than tangential force T_{max} to the rail.

The maximum force T_{max} that can be transferred depends on a large number of variables. The most important variables are: contact pressure, the substance(s) of the intermediate layer, the material that the wheel is made of, the material that the rail is made of, slip velocity, train speed and temperature (see equation 3.1).

> T_{max} = f (contact pressure, intermediate layer substance, wheel and rail material, slip velocity, train speed, temperature, wheel and rail surface roughness)
>
> Equation 3.1

The parameter of contact pressure will be handled here. The other parameters will be looked at in more detail in the following paragraphs.

Contact pressure

The maximum force T_{max} is influenced by the contact pressure. The contact pressure between the wheel and the rail is determined by the contact surface and the normal force (mainly caused by the train's mass). The wheel's diameter and the wheel and rail's profile mainly determine the contact surface. In rail transport the differences in the wheel diameter and the wheel and rail profile are generally small. In that case the adhesion will only depend on the normal force N.

It has been proven that the maximum force that can be transmitted under the given circumstances is almost proportional to the Normal force N. Equation 3.1 can therefore be written as follows:

> T_{max} = f(contact surface, intermediate layer substance, wheel and rail's material, slip velocity, train speed, temperature, wheel and rail's surface roughness)* N
>
> Equation 3.2

---

[1] *In fact adhesion is wrong terminology for indicating the extent of slipperiness between wheel and rail. A snail sticks by adhesion forces to a wall. A better term for adhesion between wheel and rail is friction. In literature about slipperiness in train environment is common to use the word adhesion in stead of friction. Therefore in this document is also used the word adhesion.*

Note that in equation 3.1 contact pressure is mentioned and that in equation 3.2 contact surface is mentioned. If the function in equation 3.2 is replaced by μ_{max} the following equation will arise

$$T_{max} = \mu_{max} * N \quad \text{Equation 3.3}$$

In this equation μ is referred to as the friction coefficient. In fact, it is not a coefficient but a function. To indicate that the maximum friction coefficient that under the given circumstances can be achieved is concerned, the subscript max has been added to μ. Equation 3.3 can also be written as follows:

$$\mu_{max} = T_{max} / N \quad \text{Equation 3.4}$$

By determining the normal force N and the force T_{max} that can just be transferred before slipping occurs, the friction coefficient μ_{max} can be determined. Note that equation 3.4 indicates that μ therefore is in fact a normalized force.

As indicated:

μ_{max} = f(<u>contact surface</u>, intermediate layer substance, wheel and rail material, slip velocity, train speed, temperature, wheel and rail surface roughness)
Equation 3.5

By continuously changing one of the variables while keeping the other values constant, the effect of the various variables on the friction coefficient can be determined. The results of this are reported in the following sub paragraphs.

3.1.1 Slip velocity

The friction coefficient is influenced by the extent at which the wheel slips in relation to the rail. This can occur during braking as well as during traction.

Definition
There are different definitions for slipping. In this document the following definitions are used for slipping during traction ($\xi_{traction}$) and slipping during braking ($\xi_{braking}$):

$$\xi_{traction} = \frac{v_{wheel} - v_{train}}{v_{wheel}} \quad \text{Equation 3.6}$$

$$\xi_{braking} = \frac{v_{train} - v_{wheel}}{v_{train}} \quad \text{Equation 3.7}$$

Dependency
Figure 3.1 curve 1 displays the friction coefficient as a function of slip speed for dry tracks with a clean running band. Such a curve is referred to as a traction curve. This figure has been retrieved from reference [11]. The figure shows clearly that the size of the slip velocity has a large influence on the friction coefficient. The traction curve 1 of figure 3.1 shows that the first part of the curve is practically straight. When slipping increases, friction increases almost proportionately. After the straight part, the curve bends increasingly faster and reaches a maximum friction value at approximately 1% slipping. The maximum achieved friction coefficient μ is approximately 0.4. After reaching this peak, the friction coefficient decreases as the slip speed increases.

3.1.2 Intermediate layer

As expected the intermediate layer, which is located between the wheel and the rails, has a large influence on friction coefficient between the wheel and the rail. Although even in dry conditions there is an intermediate layer between the steel wheel and the steel rail. This is an iron oxide layer, which is caused if steel is exposed to air. Over time this layer expands. Riding over the rail then decreases the thickness of the layer.

Depending on the intermediate layer, the form of the friction curve mentioned in §3.1.2 changes vigorously. Also, the intermediate layer has a large effect on the so-called Stribeck curve. The Stribeck curve indicates the friction coefficient at varying speeds (see figure 3.2). It will be further explained below how both curves are influenced by the substance of the intermediate layer.

Traction curve
The dependency of the type of intermediate layer on the friction coefficient is illustrated by the various curves depicted in figure 3.1. The following stands out:

- The maximum friction value μ_{max} strongly varies.
- The maximum friction value μ_{max} occurs at a different slip value (compare curve 1 and 2).
- The traction curve has not always a peak point (see curve 3).

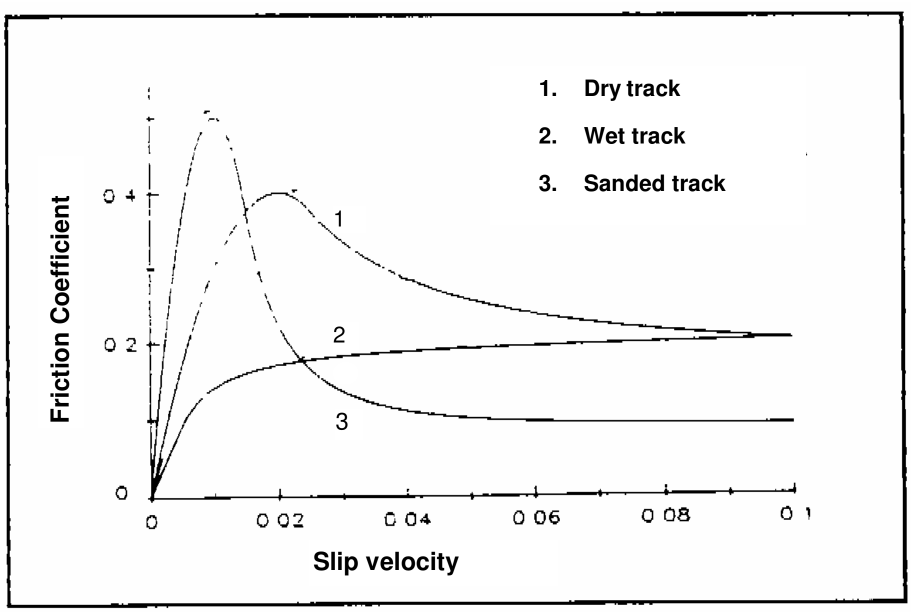


Figure 3.1 Traction curves for various intermediate layers (reference [11]).

Stribeck curve
The train speed also has an influence on the friction coefficient. Figure 3.2 shows how the friction coefficient is influenced in case of a dry rail, a wet rail and a rail covered in mineral

oil and grease. Figure 3.2 has been retrieved from reference [12] and is based on a theoretical model.

This figure shows that in case of a dry rail, speed barely has an influence on the friction coefficient. If the rail is wet the friction coefficient decreases more and more after a certain velocity (in the figure approximately 1 m/s). Because the horizontal axis has a logarithmic scale, the image of the decline is somewhat exaggerated in the figure. This is a phenomenon similar to aquaplaning with cars. In case of mineral oil or grease, the strong decline of the friction occurs at a much lower speed.

Figure 3.2 is meant to illustrate that velocity and the intermediate layer have a definite influence on the friction coefficient. Not too much attention should be paid to the different values on the axes as it concerns a theoretical model.

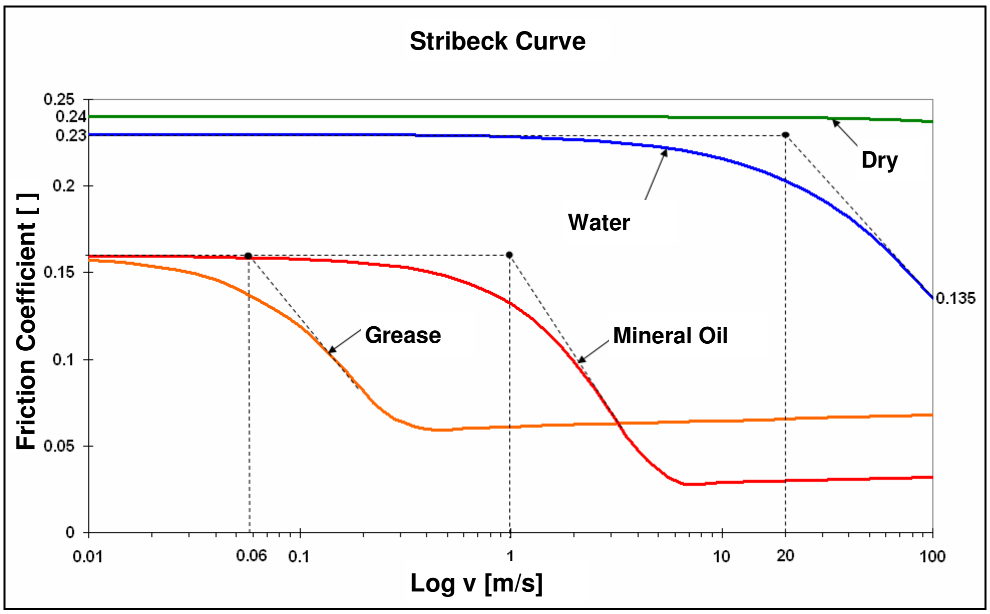


Figure 3.2 Stribeck curves, based on a theoretical model developed within AdRem.

Conclusion

The type of intermediate layer has a very strong influence on the friction coefficient (as expected). The form of the traction and the Stribeck curve depends on the sort of intermediate layer.

3.1.3 Wheel and rail material

The material of which the wheel and rail are made influences the friction coefficient. Only if a material other than steel is chosen for the wheel and rail will the friction coefficient change substantially. As long as one type of metal is chosen, the difference in the friction coefficient will be minor. For this reason the type of material is considered as given.

3.1.4 Surface's roughness

The steel wheel and steel rail's surface roughness influences the friction coefficient between both. However, if the surface has been roughened that effect will quickly disappear due to the rolling/flatting effect of the wheel on the rail and the rail on the wheel. After a few trains have driven over the roughed up tracks a surface with a low level of roughness will occur.

As long as the situation continues of a steel wheel on a steel rail where the wheel rolls over the rail with a contact pressure that is similar to that of a train, the surface roughness will be almost equal and therefore the variation of the friction coefficient will be minor. For this reason the surface roughness is considered as given.

3.1.5 Temperature

If slipping occurs between a wheel and a rail this will result in friction heat. Part of this friction heat will be transferred to the intermediate layer. This will change the intermediate layer's characteristics. By the rise in temperature, the intermediate layer's viscosity will initially increase which will reduce the friction coefficient. However, if sufficient heat is added this could lead to the layer disintegrating which will lead to an increased friction coefficient. Therefore, the temperature can strongly influence the value of the friction coefficient. The literature is not unequivocal on the exact form of the curve (see reference [10], [11], [12]).

If only small slipping percentages are measured temperature will play little or no role. In this thesis measuring focuses on low slip velocity (< 15 – 20 %) so that the factor of temperature can be left out of the equation.

3.1.6 Conclusion

If it is a matter of a steel wheel on a steel rail with contact pressure and relatively slow slip speed the friction coefficient will be determined by the intermediate layer present, by the forward speed and by the slip speed. In other words: the friction value is not a coefficient but a variable dependent on forward speed and slip speed.

3.2 Measuring principles

In order to obtain insight into adhesion on a certain part of the tracks two measuring principles can apply:

1. Determine the intermediate layer.
2. Determine the traction curve and the Stribeck curve.

Measuring principle 1

Each type of intermediate layer has a certain traction curve and a certain Stribeck curve. If the intermediate layer has been determined, the traction curve and the Stribeck curve are known. Based on both of these curves, the normal force N, slip speed and forward speed can determine the maximum force T which can be transferred to the tracks under these circumstances.

This principle requires a sensor being available to determine which substance is present on the tracks. At present a measuring tool to determine what substances are present on the track for a complete rail route is not available. As indicated in §1.3, Wageningen University is conducting a research into what is where on the track. Within the scope of this research an attempt will be made to develop such a sensor. The trouble with this principle is that in all likelihood not one substance will be present on the rail but that a mix of different substances will be found on the tracks. In order to determine low adhesion with this principle the characteristics (Stribeck curve and traction curve) of the mix will need to be known. This document will not go into this course of solution.

Measuring principle 2

Measuring principle 2 requires that the traction curve and the Stricbeck curve are determined. To determine these curves it is necessary to have a wheel available for which the normal force and the tangential force can be determined. Friction can be determined based on this. By varying the forward speed and slip velocity of the wheel, the friction value can be determined for varying slip and forward velocity. This way the Stribeck and traction curves can be determined.

3.3 Problems that occur when measuring friction

According to §3.2, measuring principle 2, to obtain accurate information about low adhesion on the tracks could be performed with a vehicle that can drive at the required speed and which is equipped with a wheel that can slip at the desired slip speed. This paragraph will show which difficulties occur during this process.

3.3.1 Statistical reliability

In practice it turns out that low adhesion does not occur very often, but that it does occur so often so that it causes inconvenience. In order to obtain insight into the problem of low adhesion a sufficient number of measurements will have to be able to be performed.

3.3.2 Continuous measurement of Stribeck and traction curve is impossible

In order to determine the friction coefficient point by point on a certain rail route it will be necessary to determine the Stribeck and traction curve of each point by using a measuring wheel. To determine the Stribeck curve and the traction curve it is necessary to determine the train's speed, the slip speed of the measuring wheel, the normal force and the tangential force. However, it is impossible to determine both the traction curve and the Stribeck curve for each measuring point. Reason of this is that it is impossible to determine the friction coefficient for each point at varying train velocities and varying slip velocities.

Also, it is impossible to measure the friction coefficient at a constant train speed at the same point at different slip speeds (of the wheel). The wheel will always have to be accelerated or decelerated for a certain amount of time. This will result in the traction curve being determined not just for one certain point, but for a distance of a few meters. It is questionable whether the intermediate layer will be the same throughout this distance. The points on the determined curve possibly might not match the same substance or amount. If the measuring route is shorter the differences in substance and amount will be smaller. A disadvantage in this is that accelerating and decelerating have to take place in a shorter length of time, which will lead to a larger development of heat. More on this subject in §3.3.3.

Conclusion
Therefore, a perfect measurement is not possible. When measuring low adhesion it will always be necessary to choose which parameters are required for measuring, for instance:

- Determining the friction coefficient at a constant speed and at the same time varying the slip velocity in time (and therefore in place). This will enable traction curves to be drawn up.
- Determining the friction coefficient at a constant speed and constant slip.

3.3.3 Required energy and heat development

To continuously measure low adhesion with a measuring wheel it is imperative that the measuring wheel slips continuously. The required energy depends on the measuring wheel's wheel load, the desired slip speed and the present friction coefficient. If the measuring wheel has a wheel load similar to that of a train a lot of energy will be required to make the wheel slip. An alternative could be to lower the measuring wheel's axel load. The question that arises then is to which extent the measuring results of a smaller measuring wheel will still be representative for a full size train wheel (see reference [12])

Another consequence of this heat development is that it influences the measurement. A measuring situation will occur that does not correspond with reality, as the temperature of the contact surface will be much higher.

3.3.4 Measuring the contact surface's temperature

As indicated in §3.1, temperature influences the friction coefficient. If low adhesion is measured constantly it will be necessary to make the wheel slip constantly. This slipping influences the heat development in the wheel/rail/intermediate layer contact. In order to obtain insight into the extent of the heat development, the temperature in the contact surface should preferably be known. Determining the temperature of the contact surface is difficult.

3.3.5 Accuracy of the slip speed

In order to determine the traction curve it is imperative to have an accurate insight into the slip velocity. In order to determine the slip velocity it is imperative to accurately know what the train (forward) speed and rotation wheel speed of the measuring wheel is. Figure 3.1 proves that on a rough track the highest friction value occurs at approximately 1%. A reasonable accuracy for determining the slip velocity is 10%. In that case it is necessary to measure the forward speed and the rotation speed with a 0.2% accuracy. This is not impossible, but will require the necessary attention.

3.4 Conclusions

It is impossible to obtain an accurate insight into the characteristics of the intermediate layer at a certain point by determining normal force, traction curve, and Stribeck curve, because this information cannot be obtained at one point. Therefore it is impossible to find an ideal solution to measure friction. The tool’s design for measuring low adhesion will always have to be based on a compromise and it will need to be adjusted to meet the intended application.

4 Literature search into methods for measuring low adhesion

Chapter 2 shows there is a need for a measurement system, which can supply practical information on low adhesion. Further along in chapter 3 it is shown why it is difficult to measure low adhesion. This chapter will show which measurement instruments have already been developed. Methods for measuring low adhesion under laboratory conditions will not be discussed. An example of a laboratory set up is the two-disc machine displayed in figure 2.19. Existing measuring instruments to gain insight into low adhesion in practice are:

- Determine braking and acceleration distance.
- LAWS (Low Adhesion Warning System).
- Automatic ride registration (ARR).
- Hand-pushed-tribometer.
- Tribo train.
- Tribo tester on vehicle.
- Stationary tribometer.
- Detection measurements.

In the following paragraphs a short explanation will be given of the various measurement tools including their most important advantages and disadvantages. Also it will be reported to which extent the measurement tool concerned can offer insight into the research questions. General information on a number of the mentioned measurement systems has been obtained from reference [13].

4.1 Determining braking and acceleration distances

The simplest way to determine the average adhesion of a slippery track is by making a train slip on a slippery track. Based on initial speed, final speed (usually 0 km/h) and braking distance the average deceleration of a train can be determined. According to equation 4.1 the friction coefficient μ can be determined by dividing the average deceleration by the gravitation acceleration g. Naturally this method can be applied for acceleration also. In that case it must taken into consideration that not all axes are driven. To determine μ for acceleration the fraction a/g in equation 4.1 has to be multiplied by k in which k is total amount of axles divided by the number of driven axles.

$$\mu = \frac{m_{train}\, a}{m_{train}\, g} = \frac{a}{g} \qquad \text{Equation 4.1}$$

The advantages for this measurement method are:

- Simple measuring tool (inexpensive).
- Easy insight into average friction coefficient.

Major shortcomings are:

- It only allows for the average friction coefficient to be determined over a certain distance.
- Roughing effect of the wheels is not taken into account.
- It is not possible to conduct a large number of tests.

4.2 LAWS

From 1999 until 2006 LAWS (Low Adhesion Warning System) was installed in 17 trains of 7 different types of trains. The deployment of these types of trains on the Dutch railroads was arbitrary. If slip (braking/traction) was measured LAWS recorded the following information: time, location (GPS), breaking/traction conditions and speed. This information was sent to a central computer. That computer determined how serious a certain slipping incident was based on how long the slipping lasted. If a certain limit was crossed drivers in the vicinity of the slippery location were warned via text messages. In 2007 most systems were dismantled due to the fact that LAWS did not report enough slippery incidents.

In addition to sending out warnings to the drivers an attempt was made to gain insight into the effectiveness of Sandite and sanders by using the LAWS data. LAWS was also used to find out where and when it was slippery. This research has not given much in side in low adhesion.

Table 4.1 shows whether LAWS is capable of answering the research questions. The major advantages of LAWS are:

- Relatively simple measuring tool (inexpensive).
- Measurements are made in passenger trains running in service which allows many measurements to be made.
- Slipping is recorded both during braking as well as during acceleration.
- It is possible to demonstrate a connection between low adhesion and operation by the driver.

Major shortcomings are:

- Impossible to measure the extent of low adhesion.
- LAWS does not register any information if it is not slippery.

Research question	Does LAWS offer insight into the research question?	Remarks
2. How does the present braking system perform?	Yes	The acquired insight is incomplete because LAWS cannot determine how slippery it is.
3. Is the driving on time dip in the fall caused by low adhesion? If yes, is this dip caused by acceleration or braking? And what is the influence of driver's behaviour on acceleration and braking performance?	No	Cannot be judged because LAWS does not report any data if it is not slippery.
4. Where and when is it slippery?	Yes/No	LAWS can indicate where and when it is slippery, but not to what extent?
5. How fast can low adhesion occur and to which extent does low adhesion occur in various locations?	No	LAWS does not record any data if it is not slippery, therefore it cannot be determined if a measuring train has passed a certain location and has not recorded low adhesion.
6. What is the effectiveness of present measures?	No	LAWS does not offer any insight into the roughing effect of the measure because LAWS cannot measure the extent of the low adhesion.

Tabel 4.1 Insight by LAWS data.

4.3 Automatic Ride Registration (black box)

All trains in The Netherlands are equipped with Automatic Ride Registration (ARR), which in fact is a black box. The ARR's primary task is to record data that can help explain why an accident has happened when a train is involved in one. The ARR functionalities differ per type of train but can always register the following information: ATB signal code, speed, distance travelled, time of first braking, speed brake and ABI activity. Information on these parameters is recorded every second. The ARRs used in the Netherlands can store information for 24 hours.

In Germany the ARR is read after each maintenance overhaul (storage term there is approximately 3 months) in order to gather insight into the braking distances that occur in practice. This way they can connect low adhesion (WSP activity) and braking distance distribution.

Major advantages of using ARR are:

- Relative simple measurement tool (inexpensive).
- Measurements are taken from passenger trains running in service enabling many measurements to be taken.
- Slipping is recorded both during braking as well as during acceleration.
- Registration is made even when it is not slippery.

Major shortcomings are:

- Extent of the low adhesion cannot be registered.
- The ARR only offers a limited insight into the operations applied by the driver.

In view of the short storage time of the Dutch ARR for this research the ARR will need to be equipped with a read-out system and a board-land connection. As the ARR is part of a safety relevant system it is not possible to simply read-out the ARR automatically. A failure analysis will have to be conducted first. Table 4.2 shows to which extent the ARR is capable of answering the research questions.

Research question	Does the ARR offer insight into the research question?	Remarks
2. How does the present braking system perform?	Yes	The obtained insight is incomplete because ARR cannot determine how slippery it is.
3. Is the driving on time dip in the fall caused by low adhesion? If yes, is this dip caused by acceleration or braking? And what is the influence of driver's behaviour on acceleration and braking performance?	No	ARR offers insufficient insight into the applied braking position and no insight into the applied traction position.
4. Where and when is it slippery?	No	ARR cannot answer where and when it is slippery nor to what extent.
5. How fast can low adhesion occur and to which extent does low adhesion occur in various locations?	No	ARR cannot determine where the train is and therefoe cannot determine differences in low adhesion per location or in time.
6. What is the effectiveness of present measures?	No	The ARR cannot offer insight into the roughing effect by the measure because the ARR cannot measure the extent of low adhesion.

Tabel 4.2 Insight by ARR data.

4.4 Hand-pushed-tribometer

The hand-pushed-tribometer (see figure 4.1) is a relatively small device that is pushed by a person. The hand-pushed-tribometer is equipped with a measuring wheel that is slowed down until slipping occurs. the friction coefficient is determined based on the load that is put on to the wheel and the force required to make the wheel slip. Nowadays there are versions available that can determine the traction curve. Because the measuring wheel has different dimensions and due to the fact that other contact pressure is involved the measured friction coefficients are different to a measurement conducted with a full size train wheel.

Table 4.3 shows whether the hand-pushed-tribometer is capable of answering the research questions. Major advantages of the hand-pushed-tribometer are:

- Relative simple measurement tool (inexpensive).
- Flexible use at desired location of measurement.
- Offers insight into the extent of low adhesion.

Major shortcomings are:

- Labour intensive.
- In the Netherlands a railway line must be shut down during measurements.
- Accuracy of the measurements is low.

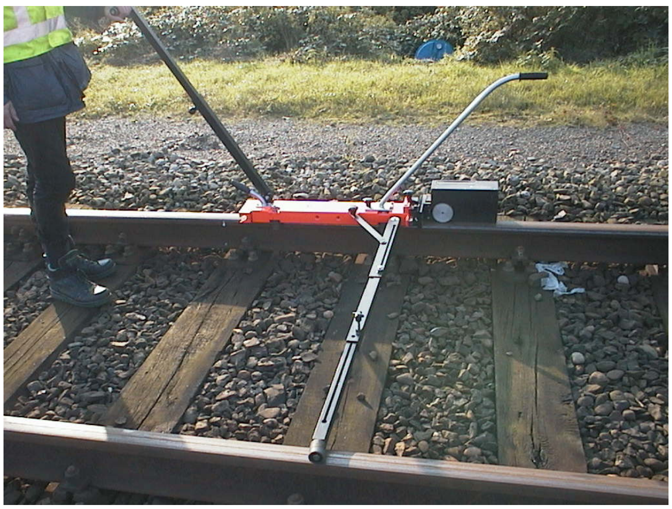


Figure 4.1 Hand-pushed-tribometer.

Research question	Does the hand-pushed tribometer offer insight into the research question?	Remarks
2. How does the present braking system perform?	No	Measuring system is not connected to a train
3. Is the driving on time dip in the fall caused by low adhesion? If yes, is this dip caused by acceleration or braking? And what is the influence of driver's behaviour on acceleration and braking performance?	No	Measuring system is not connected to a train
4. Where and when is it slippery?	Yes/No	Insight at 1-2 stations is possible, but is labour intensive
5. How fast can low adhesion occur and to which extent does low adhesion occur in various locations?	Yes/No	Insight at 1-2 stations is possible, but is labour intensive. Determining low adhesion at varying locations is practically impossible
6. What is the effectiveness of present measures?	No	The hand-pushed-tribometer's accuracy is insufficient

Tabel 4.3 Insight by hand-pushed-tribometer.

4.5 Tribometer train

In this report a tribometer train is defined as a train, which uses its existing train wheels to measure the friction coefficient. During the 70's various research was conducted using this method. The first research was conducted by British Rail and was aimed at obtaining insight into where and when it was slippery (see reference [15]). The second research was conducted by ORE under the authority of UIC and was aimed at increasing insight into the effect of low adhesion during acceleration of (freight) locomotives (reference [16] and [17]).

The British Rail tribometer train increasingly slowed a train wheel down until it slipped. As soon as slipping occurred the brakes were taken off. The friction was determined based on axle load and by measuring the horizontal force that the brakes put on to the axle bearing. Reference [18] shows a Japanese patent that is very similar to the British Rail tribometer. The ORE triboter train was more complex (see mentioned references) and was also capable of making traction curves and Stribeck curves.

Table 4.4 shows whether a tribometer train is capable of offering insight into the research questions. Major advantages of a tribometer train are:

- Measures the friction coefficients under actual circumstances, with the same wheel load and size.
- Slipping can be recorded if necessary during breaking and/or acceleration.

Major shortcomings are:

- Measurement is done from a special measurement train; it is therefore expensive to perform many measuring trips.
- Because measurements are not done from a passenger train running in service no connection can be made between low adhesion and operation by the driver.
- Complex measuring tool (expensive).
- High energy use.

Research question	Does the tribometer train offer insight into the research question?	Remarks
2. How does the present braking system perform?	No	Measuring tool cannot be built in into passenger train running in service
3. Is the driving on time dip in the fall caused by low adhesion? If yes, is this dip caused by acceleration or braking? And what is the influence of driver's behaviour on acceleration and braking performance?	No	Measuring tool cannot be built in into passenger train running in service
4. Where and when is it slippery?	Yes	One measuring train is insufficient to obtain insight
5. How fast can low adhesion occur and to which extent does low adhesion occur in various locations?	Yes	It is possible but the measuring trains must be able to perform sufficient measurements on a limited number of locations
6. What is the effectiveness of present measures?	Yes	

Tabel 4.4 Insight by tribometer train.

4.6 Tribo tester on vehicle

Using full size train wheels to measure friction has two major setbacks. First: the large amount of energy required to make a wheel slip. Secondly, due to the fact that the train wheels on the left and right are connected by a rigid axle (wheel set) only the average friction of both rails can be determined and not that of one of each separate rail. Attaching a separate tribometer to a train or coach can compensate for both disadvantages. Portec's triborailer (see figure 4.2) is an example of this. Another example can be found in the patent literature (see reference [19]). In Sweden one of the wheels of a grinding machine was used to measure low adhesion.

In the rail sector high value is attached to safety and reliable execution of the timetable. Therefore the train operating companies exercise restraint when it comes to placing complex devices to the outside of a passenger train running in service. During development of a tribo tester for a train it must be taken into account that The Netherlands will not permit a tribo tester to be installed on a passenger train running in service. Table 4.5 shows whether a tribo tester on a special test train or test vehicle is capable of offering insight into the research questions

Within the scope of the research program AdRem the chair Tribology of the Twente University developed a tribo tester to verify the wheel/rail/contact model, which they developed and in order to obtain information about the intermediate layer's characteristics as they occur in practice. Further details regarding this tribo tester can be found in §8.2.


Figure 4.2 Portec's tribo railer.

Major advantages of a tribo tester on a vehicle/train are:

- The friction coefficient can be determined accurately.
- The traction curve can be determined.
- The friction coefficient can be determined during braking and/or traction.

Major shortcomings are:

- Complex measuring tool (expensive).
- Scaling errors may occur due to the fact that the size of the wheel and wheel load are not equal to that of a train wheel.
- Because of the special measuring train it is impossible to make a connection between low adhesion and the driver's behaviour.

Research question	Does the tribo tester offer insight into the research question?	Remarks
2. How does the present braking system perform?	No	Measuring tool cannot be built in into passenger train running in service
3. Is the driving on time dip in the fall caused by low adhesion? If yes, is this dip caused by acceleration or braking? And what is the influence of driver's behaviour on acceleration and braking performance?	No	Measuring tool cannot be built in into passenger train running in service
4. Where and when is it slippery?	Yes	One measuring train is insufficient to obtain insight
5. How fast can low adhesion occur and to which extent does low adhesion occur in various locations?	Yes	It is possible but the measuring trains must be able to perform sufficient measurements on a limited number of locations
6. What is the effectiveness of present measures?	Yes	

Tabel 4.5 Insight by tribotester.

4.7 Stationary tribometer

In order to be able to monitor low adhesion at a certain location it would be interesting to be able to measure the friction coefficient from the track. Reference [20] describes a method that can measure the friction coefficient using sensors that are installed in curves. The measuring method is based on the fact the forces that are enforced by a bogie on the rail, especially in curves, are not the same for a rough rail as for a slippery rail. In case of a rough rail the self-steering effect of the bogie is larger than for a slippery rail.

This self-steering effect occurs due to the fact that a torque occurs in the bogie by the wheels' iconicity, by the fact that the left and right hand wheel are rigidly connected and due to the fact that the axes in the horizontal surface are connected rigidly to the bogie. In the mentioned reference this difference in force has been measured from the rails by using force sensors (strain gauges). This difference in force can also be measured from the train (see reference [12]). The value measured must be scaled to a value that is the same as the friction values of a train wheel's rolling friction.

Table 4.6 shows whether the stationary tribo meter is expected to be able to offer insight into the research questions. Major advantages of a stationary tribo meter are:

- Many measurements can be taken; friction can be measured for each train passage.
- The friction coefficient can be measured under actual circumstances with the same wheel load and size.
- Requires relatively simple measuring tools.

Major shortcomings are:

- Only possible to measure in curves of wheels that are not being driven or braked.
- Because measurements are taken from the track it is impossible to make a connection between low adhesion and driver behaviour.
- Impossible to determine a traction curve.

Research question	Does a stationary tribometer offer insight into the research question?	Remarks
2. How does the present braking system perform?	No	Measurements take place from the infrastructure so that no information on the train is available
3. Is the driving on time dip in the fall caused by low adhesion? If yes, is this dip caused by acceleration or braking? And what is the influence of driver's behaviour on acceleration and braking performance?	No	Measurements take place from the infrastructure so that no information on the train/driver's behaviour is available
4. Where and when is it slippery?	Yes/No	Low adhesion can only be determined for the locations where the measuring system has been installed
5. How fast can low adhesion occur and to which extent does low adhesion occur in various locations?	Yes	In the location where a measuring system is present it is easy to monitor the development of low adhesion over time.
6. What is the effectiveness of present measures?	Yes/No	Very suitable for assessing effectiveness of location-dependent measures

Tabel 4.6 Insight by stationary tribometer data.

4.8 Measuring intermediate layer's electrical resistance

It is important to know if a train is located in a certain section of the railways. Based on that information can be avoid another train from entering the same section. Detection from a train in a certain section takes place when a wheel set causes a short-circuit between the left and the right hand rail. However, if the rail is polluted the pollution can become an isolating layer making it impossible for electricity to run from the right hand rail, through the wheel set to the left hand rail. As a result chances are high that a train cannot be detected which could lead to an accident happening. In order to investigate how large the chance is that a train cannot be detected a measuring train (see reference [22]) has been developed that can measure the resistance between the two rails. In case of high resistance there is an increased chance that the train will not be detected.

This technique could also be used to identify where and when there is pollution on the track. Substances on the track might lead to low adhesion. Research (see reference [23] and [24]) shows that if an intermediate layer has been formed as a result of low adhesion, the intermediate layer is more slippery than a clean and dry rail. The rail becomes really slippery when the intermediate layer moisten (becomes a little bit wet by dew, rain, etc). An advantage of measuring the intermediate layer's resistance is that all potentially slippery track can be found. However, if the intermediate layer becomes wet/damp/moist (and therefore really slippery) the resistance will go down and a smaller intermediate layer (slipperiness) will wrongfully be measured.

Table 4.7 shows whether this method is expected to be able to offer insight into the research questions. Major advantages of detecting an intermediate layer by measuring electrical resistance are:

- Relatively simple measuring tool (inexpensive).
- Measured from a passenger train running in service allowing for many measurements to be taken.

Major shortcomings are:

- The extent of the low adhesion cannot be registered.
- The connection between resistance and low adhesion might be disappointing.

Research question	Does this method offer insight into the research question?	Remarks
2. How does the present braking system perform?	No	Cannot measure how slippery it is
3. Is the driving on time dip in the fall caused by low adhesion? If yes, is this dip caused by acceleration or braking? And what is the influence of driver's behaviour on acceleration and braking performance?	No	Low adhesion is not measured; therefore no connection can be made between low adhesion and acceleration/braking and operation by the driver
4. Where and when is it slippery?	Yes/No	The resistance method might offer insight into where and when an intermediate layer with high resistance is present. The method cannot determine whether that layer can lead to low adhesion and certainly not to what extent the layer is slippery
5. How fast can low adhesion occur and to which extent does low adhesion occur in various locations?	No	Because low adhesion and resistance depend very much on moisture it is expected that the resistance method will not offer insight into how fast low adhesion can change in certain places
6. What is the effectiveness of present measures?	Ja/No	The resistance method might offer insight into whether the intermediate layer has been removed/decreased because of a certain measure. However, there are other measures such as sanders that actually cause a thicker intermediate layer

Tabel 4.7 Insight by intermediate layer's electrical resistance data.

4.9 Conclusions

This chapter shows that measuring low adhesion is difficult. It also has become apparent that until now no measuring tools are available that can offer insight into the extent of the low adhesion from inside passenger train running in service. Measuring devices that are very capable of monitoring the parameters relevant for low adhesion cannot determine the extent of the slipperiness.

It appears that the measuring methods that can accurately determine the extent of low adhesion are only moderately capable of monitoring. The reason for this is because the accurate devices require high investments which make converting some trains too expensive. Moreover, for safety reasons it is virtually impossible to install complex measuring devices outside passenger trains running in service. Measurements made by a special test train would therefore be required which has a large influence on the costs.

Therefore none of the existing measurements tools are suitable to offer insight into the research questions unless a high budget for research is made available.

5 Developing a suitable measurement system

As mentioned in chapter 3 in order to obtain insight into the research questions a measurement method will be necessary. A measurement method is a measuring tool combined with a measurement set-up. The measurement set-up is how a measuring tool is deployed.

§5.1 will show which requirements and wishes the measurement method must meet. As none of the existing measurement tools meet the requirements, the measurement tool that is to be developed which will meet the requirements is described in §5.2. In §5.3 the idea behind the measurement system will be described in further detail. §5.4 will offer insight into accuracy of the measuring system. Finally in §5.5 conclusions will be drawn.

5.1 Anticipated requirements for the measurement system

In this paragraph the desired requirements for the measurement system will be discussed which should lead to insight into the research questions mentioned in chapter 2.

Anticipated requirements regarding research question 2
Research question 2 is: *How does the current braking system perform?*

In order to obtain insight into the braking system's effectiveness on a slippery track, it is necessary to know which braking level the driver chose, the deceleration that occurred and whether it was slippery when the driver applied the brakes.

Anticipated requirements regarding research question 3
Research question 3 is: Is the driving on time dip in the fall caused by low adhesion. If yes, is this dip caused by acceleration or braking. And what is the influence of driver's behaviour on acceleration and braking performance?

In order to be able to determine the loss of travel time due to low adhesion a relation must be made between low adhesion and the time it takes to cover a certain route. This requires determining whether the travel time for the route is extended by decreased traction acceleration or decreased braking deceleration. At the same time it must be made clear how the train is operated by the driver.

In order to avoid having to combine various files from various measuring tools it would be preferred if all information was gathered by the same measurement train. In order to be able to make a reliable judgement it is necessary to get sufficient measurements on the routes, which are to be researched.

In summary; in view of this research question it would be advisable to get insight into the following parameters: the extent of the low adhesion, the train's acceleration and deceleration and the braking and traction levels that were chosen by the driver.

Anticipated requirements regarding research question 4
Research question 4 is: *Where and when is it slippery and to what extent?*

In order to know where and when it is slippery the network must be monitored by a sufficient number of measurement trains. It would be advisable to conduct measurements throughout the fall season and also during a similar period in another season. The latter is necessary in order to know if low adhesion actually occurs less often beyond the fall than it does in the fall.

Anticipated requirements regarding research question 5

Research question 5 is: How fast can low adhesion occur and to which extent does low adhesion occur in various locations? In other words: how predictable/measurable is low adhesion?

In order to obtain insight into how quickly low adhesion can occur it is necessary to perform a vast number of measurements for low adhesion on slippery days at one or more stations. Preferably, on a slippery day, measurements should be conducted every hour.

In order to find out if low adhesion often occurs in the same locations or rather that it occurs in varying locations, it would be advisable to conduct measurements at as many Dutch stations as possible.

To meet both demands would require a large number of measurement trains. From a cost point of view this is not a feasible option. In order to answer both research questions to a certain extent it is probably wise to focus on a limited number of stations but to conduct many measurements per day at those stations.

Anticipated requirements for research question 6

Research question 6: What is the effectiveness of the current measures? Is it possible to guarantee a minimum braking distance with these current measures?

In order to obtain insight into the effectiveness of the measures taken to reduce the problems caused by low adhesion would require having measurement tool(s) installed on (a) passenger train(s) running in service to measure low adhesion. If the measures to be taken depend on the situation (for instance magnetic track brakes) it would be ideal to have at least 2 measuring tools per train for measuring low adhesion. The first measuring tool could measure low adhesion before measures have been taken. The second measuring tool can measure the low adhesion after measures have been taken. The difference between both measurements will indicate the effectiveness of the measures taken.

If the measures to be taken depend on the location (for instance Sandite) it will be necessary to have at least 2 stations where the problems caused by low adhesion occur are similar. In that case, one station could act as testing station where certain measures have been taken and the other station could act as reference station. The difference in the occurrence of low adhesion at both stations will offer insight into the effectiveness of the measures taken. In order to make this equation it is necessary that the adhesion at both stations is measured regularly. It would be advisable to conduct hourly measurements for low adhesion at those locations.

Summary of the preferences

The above leads to certain preferences regarding the measuring system and measuring method. These preferences have been summarized below. The preferred parameters to measure are:

1. Level of adhesion (friction coefficient).
2. Braking deceleration and traction acceleration.
3. Driver’s braking and traction behaviour.
4. Location.
5. Time.

Preferences regarding the measurement set-up:

1. The chance to collect the preferred parameters for the period of a few weeks in the autumn and a few weeks beyond the autumn.
2. Conduct measurements at all stations along one route with at least five measurements per day at each station.
3. Ability to monitor when it is slippery but also when it is not.
4. Ability to conduct measurements from (a) passenger train(s) running in service.
5. More than one friction measurement per train.
6. Deployment of measurement trains along a fixed research route.

Precondition is:

1. The measurement system may not intervene with safety and operational reliability (disruption of the train service).

Preconditions within the project are:

1. Acceptable price.
2. Achievable within a limited length of time.
3. An achievable design (certainty that it will work).

Conclusion
It would be desirable to have a measurement system that can offer insight into how a train performs and how it is operated by the driver during low adhesion. In summary: performance monitoring during low adhesion.

5.2 General description of the VIRM tribo meter train

In §4.9 the conclusion was drawn that the existing low adhesion measurement systems are not capable of offering insight into all research questions. After extensive research of all the systems used in the various trains an interesting, relatively simple method has been found which fulfils, as best as could be hoped for, all the preferences described in §5.1. This method uses the information already measured by the trains. Most of the information is transmitted to the diagnosis system, which supplies the staff of the train with the required information. For instance information necessary for driving a train, but it could also be information regarding malfunctions.

This method is simple and inexpensive because it predominantly uses information, which already is available on the train. Such diagnosis systems are available on most of the NS' modern trains: the stop train double-decker, Buffel, Region Runner (VIRM) and the new sprinter (SPL). This thesis focuses on the VIRM. This paragraph describes how the system works and which information is gathered.

5.2.1 Specification of the measurement system: VIRM as tribo train

This paragraph describes how the measurement system that is to be developed will operate. Figure 5.1 shows a schematic of the measurement system.

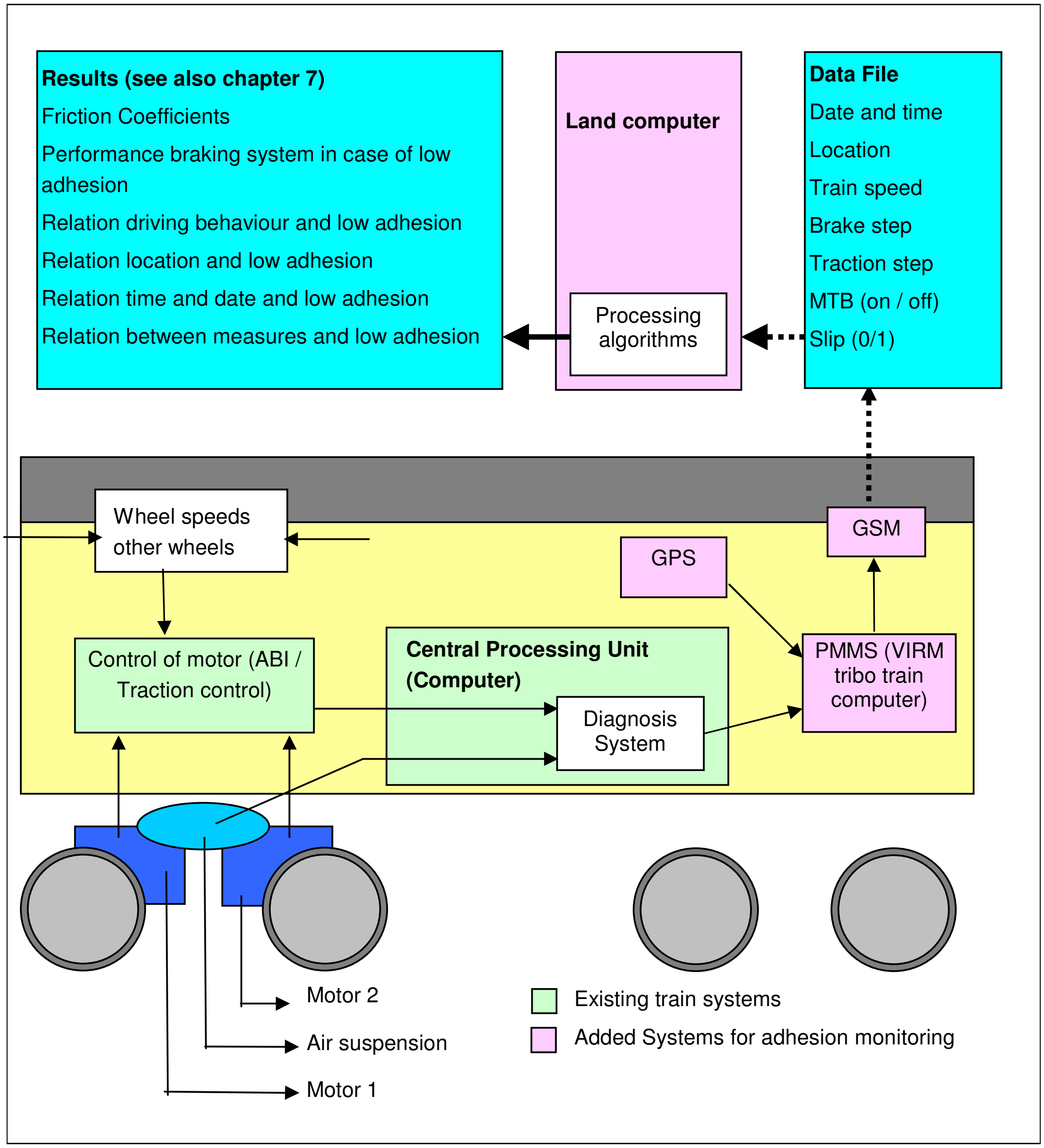


Figure 5.1 Schematic of the concept VIRM tribo train.

Traction installation and ED-brake

The traction installation (motor) is used to drive the train. The VIRM trains also use the motors for braking. This type of braking system is also called an ED-brake (Electro Dynamic brake). If the wheels slip during acceleration, the traction control ensures that the motor torque is decreased so that slipping is reduced. If the wheels slip during braking the WSP (Wheel Slide Protection) makes sure that slipping is reduced. While driving, the traction control determines the level of motor torque, both during acceleration as well as during braking. The motor torque is transmitted to the diagnosis system, which is part of the train's central computer.

Determining friction
The friction coefficient is defined as the horizontal force that the train wheel can just convey to the tracks divided by the vertical force. In other words: braking/traction force divided by normal force (see equation 3.4). In order to determine both of these forces, the measured variables of the motor torque and axle load are used; they are both proportional to the horizontal and vertical force. As the motor can apply traction and braking torque (ED-braking) the friction coefficient of the tracks can be determined during acceleration as well as during braking. The friction coefficient can only be determined if slipping of the wheels occurs (during acceleration or braking). This will be further elaborated in §5.5.

The pressure sensors in the bellows of the air suspension determine the axle load (N). The air bellow's control unit also transmits the air bellow's measuring signal to the diagnosis system.

As previously indicated, the friction coefficient can only be determined if slipping is detected by the traction control or the WSP. Whether slipping has occurred is determined by the traction control based on the motor's rotation velocity and the other axes' rotation speed. Information about whether or not the wheels are slipping is transmitted to the diagnosis system. For this research into low adhesion it is not a problem that the friction coefficient cannot be determined in places where it is not slippery because apparently there are no problems there, as the train does not slip in those places.

Diagnosis system
The diagnosis system is part of the central computer. This system collects information from the sensory in the train and indicates the status of the sub systems in the train and any malfunctions that occur. The diagnosis system collects information from approximately 4.000 parameters.

GPS
In order to make correlations between low adhesion and location it is necessary to equip the measurement trains with GPS.

Other parameters
In order to be able to answer the questions raised in chapter 2 information about parameters other than adhesion and location are required, such as: date and time, train speed, chosen braking level (step), chosen traction level (position), activated emergency brake, activated magnetic track brake. This information supplied by the diagnosis system is standard.

PMMS
A special computer, PMMS (preventive maintenance and malfunction diagnosis system) has been installed in order to enable the read out of information from the diagnosis system. The name derives from the project that initially developed the system. PMMS also collects information on location via GPS. After read out, the PMMS computer uses GSM to transfer information to the land computer. Figure 5.2 shows pictures of the PMMS computer in the train.

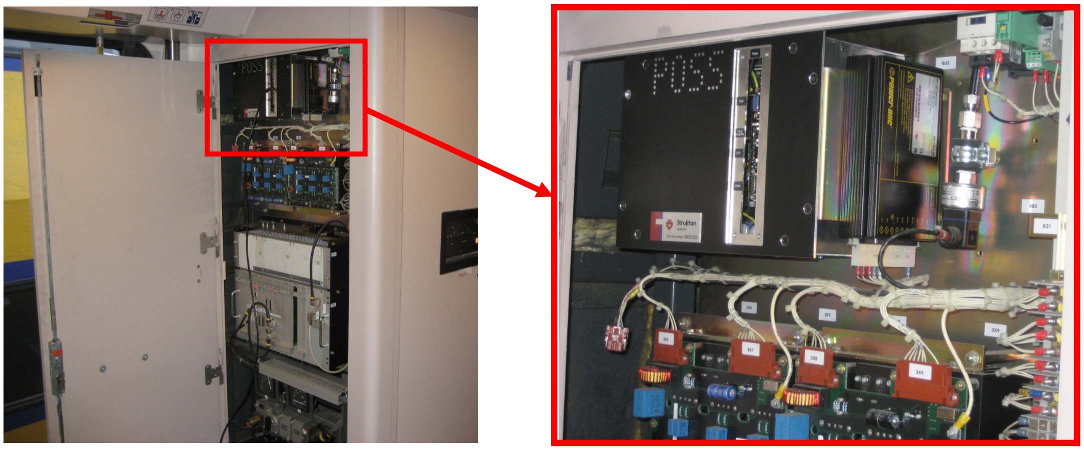


Figure 5.2 PMMS computer installed in the train.

Land computer

The land computer receives the required information (see §5.2 and §7.1) from PMMS. In order to answer the research questions, the measurement information is processed by using the algorithms that make the necessary relations.

Pros and cons of the VIRM as tribo train

The most important pros and cons of the measurement tool VIRM Tribo train are listed below

Advantages

1. Measures from a passenger train running in service; this allows measurements to be conducted under daily circumstances.
2. Allows a large number of measurements to be conducted because they are done from within a passenger train running in service.
3. Inexpensive measurement tool, this allows it to be installed on multiple trains enabling a large part of the network to be monitored.
4. A special measurement train is not required (which is expensive and requires extra deployment).
5. More than one tribometer per train.

Disadvantages

1. Adhesion measurement can only be done where slipping occurs (both during braking as well as traction).
2. Limited possibility to make traction curves. This functionality is not relevant for this research.

5.2.2 Measurement data on tribo trains

In order to be able to answer the research questions stated in chapter 2 the practical information collected by the VIRM tribo trains will be reported in a table. §5.2.1 shows where the various measurement data come from. The VIRM tribo train supplied the following measurement data:

1. Rolling stock number from which the measurements were collected.
2. Date and time.
3. GPS coordinates
4. Applied motor torque traction installation 1 (in front coach 1), 2 (in rear coach 2) and 7 (in middle coach).
5. Axle load bogie 1, 2 and 7.
6. Slipping of motor bogie 1, 2 and 7.
7. Train speed.
8. Braking level.
9. Emergency brake activated.
10. Magnetic track brake activated.

Sample time

The sample time is the time that passes between two subsequent measurements of similar variables. The sample time for the diagnosis system is 1s; the sample frequency is therefore 1 HZ. The supplied values are not average values for that second but a momentary value for that time point.

Information related to the traction installation/ED brake can also be immediately read out of the traction installation / WSP's control. This could be any of the following information: applied traction/braking torque, slipping of the traction installation/ED brake and overhead cable tension. An advantage of reading out the traction installation/ED brake is that the sample frequency is much higher: approximately 10 Hz. A proof of principal (chapter 6) will need to prove which frequency is required.

5.3 Detailed description of the measurement system

This paragraph describes in more detail how the measurement system works.

5.3.1 Principle of VIRM tribo train

§5.2 shows in general where the measurement data to determine the extent of adhesion have come from. This paragraph describes in further detail the VIRM tribo train's measuring method. The most important parameter that needs to be determined based on the information from the diagnosis system is the friction coefficient μ_{max}. In order to determine the friction coefficient by using the concept of the VIRM tribo train 3 parameters are important: tangential force T, the axle load and whether the bogie concerned slips.

Determining friction

In figure 5.3 the red line shows the maximum friction μ_{max}., which theoretically occurs under certain circumstances on a certain railway route. As depicted in this figure, the value varies in distance.

In order to brake, maintain a certain speed or accelerate a train's wheels must apply a required force $F_{required}$ to the rails. In order to transmit this force a certain minimum friction $\mu_{required}$ is required between the wheel and the rail; the black dotted line in figure 5.3 shows $\mu_{required}$

Until point A, the required friction $\mu_{required}$ is smaller than the friction present μ_{max} and the wheels can apply the required force $F_{required}$ by the driver to the rails. After point A that is no longer the case, the friction coefficient μ_{max} is lower than the required friction coefficient $\mu_{required}$, which will lead to the wheels slipping (during traction or braking). The traction control/WSP will attempt to utilize the present adhesion as best as is possible. Based on the slip velocity determined, the motor torque will be adjusted. The traction control will reduce the force by the wheel on the rail from $F_{required}$ to $F_{applied}$. Therefore a lower friction will be required: instead of $\mu_{required}$ only $\mu_{applied}$ will be required. Subsequently by increasing and decreasing the motor torque, the WSP and the traction control will search for the maximum force that can just be conveyed to the tracks in order to meet the driver's wishes. Increasing and decreasing the motor torque will lead to the "shark tooth" curve for $\mu_{applied}$ (the blue line)

The smaller the deviation from the "shark tooth" curve compared to the curve of the actual friction μ_{max} the more effective the WSP or the traction control will be on slippery tracks and the better it is for determining the actual friction coefficient.

Determining $\mu_{applied}$ is simple. According to equation 3.5 it is:

$$\mu_{applied} = \frac{T_{applied}}{N} \qquad \text{Equation 5.1}$$

To determine $\mu_{applied}$ the forces N and $T_{applied}$ need to be determined. This is discussed in further detail below.

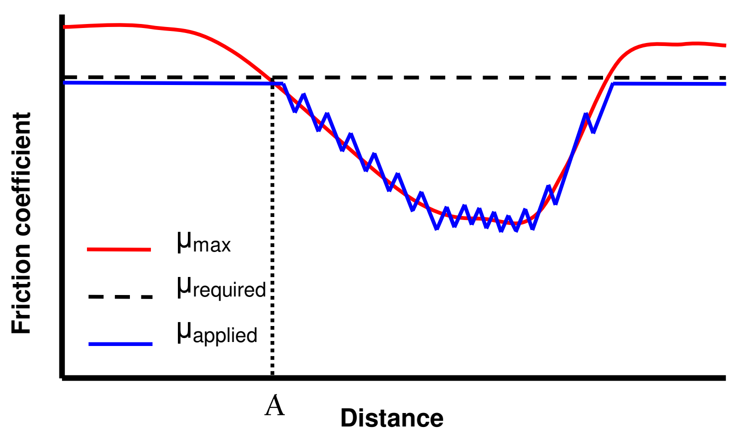


Figure 5.3 Friction coefficient as a function of the distance.

Determining tangential force

The diagnosis system can determine the level of the applied motor torque from moment to moment. If slipping does not occur (traction or braking) the brake/traction torque equals the torque applied by the driver. If slipping does occur the traction control/WSP will determine the maximum transmittable torque. If the traction/brake torque $M_{applied}$ is multiplied with the transmission ratio I of the gearbox and divided by the wheel's radius ½ d then the tangential force $T_{applied}$ that the wheel applies to the rail can be determined.

$$T_{applied} = M_{applied} \times \frac{2i}{d} \qquad \text{Equation 5.2}$$

The constant values here are:

i	4,29 (73/17)
d	0,880 m

Gearbox friction

In equation 5.1 the gearbox's output (friction) has not been taken into account. The gearbox's output is 97%. If this output is taken into account equation 5.3 will arise.

$$T_{used} = c \times M_{used} \times \frac{2i}{d} \qquad \text{Equation 5.3}$$

c during traction is 0,97 and during braking is 1,03.

Remark

Equation 5.3 does not take into account the effect of inertia of the motor axle, gearbox and wheel sets. This equation takes not in account the fact that the wheel diameter can vary, also. §5.5.4 will show why this neglect is acceptable.

Determining normal force

The normal force N that the wheel applies to the rail is caused by the train's mass and by dynamic forces. The dynamic forces occur as a result of a vertical or horizontal movement by the train for instance due to a bend or a dent in the tracks.

Dynamic forces will not have a major effect on the outcome. Due to the dynamic forces, the measured normal force will in actual fact be larger on one occasion and less on the other. In the end, the average value will equal the statistical value. If sufficient measurements are conducted per time unit (sample time) the error margin will be minor. The horizontal forces also will not have a large effect because they are minor compared to the statistical vertical force. Another reason is that when curves are taken at high speed, super-elevation will occur which will compensate for this sideway force.

Dynamic forces have not been taken into consideration in this project. In that case, the normal force N is only determined by the train's mass. The diagnosis system receives information about the bogie's load from the pressure sensors in both air bellows. Based on this information the diagnosis system determines the mass. By multiplying the mass with 9,81 m/s^2 normal force N arises.

Determining slip

As previously indicated, the friction coefficient can only be determined if slipping of the wheels (traction or braking) occurs. For this reason it is important to know if the wheels are slipping. Whether slipping occurs is determined by the traction control based on the rotation speed of the motor axle and the rotation velocity of the train's other axes. Information regarding whether or not the wheels of the motor bogie concerned is slipping is transmitted to the diagnosis system.

Remark

In chapter 6 a proof of principle will be conducted which must prove that the suggested measuring system works.

5.3.2 The measuring range

If a train's motor is required to apply a high traction or braking torque a higher friction is required to convey the required force with the wheel than if a low traction/braking torque is required. The difference in the required torque also affects the measuring range of the friction coefficient that can be reached with the VIRM tribo trains.

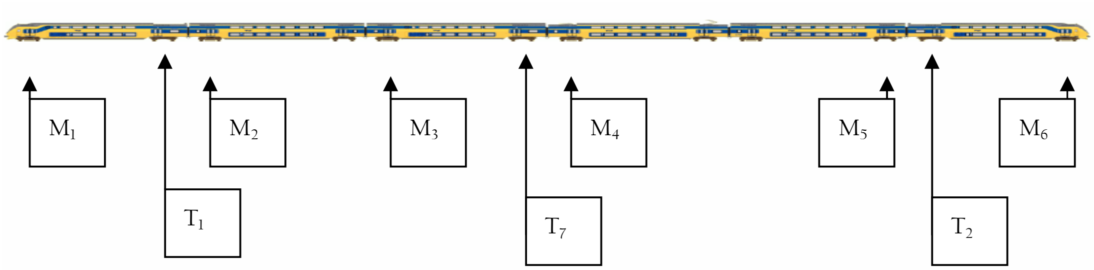
Suppose the motor applies a traction/braking torque, which requires a minimum friction of 0.18 it is possible to use the VIRM tribo train principle to measure the friction values μ_{max} ranging from 0 to 0.18. If the motor applies a lower traction/braking torque for which for instance a minimum friction of 0.06 is required then it will only be possible to measure friction values between 0 and 0.06. The following aspects influence the motor torque: driver's driving behaviour, speed, and overhead cable voltage. In this paragraph these subjects will be discussed in further detail.

Choosing traction handle

The traction handle can be infinitely adjusted. The driver can choose any traction torque between 0 and 100%. If a driver applies 100% traction then the 3 bogies combined will result in a tractive force of 213.9 KN on the wheel surface (see reference [25] and [26]. By applying equation 3.5 it becomes evident that at an axle load of 17.000 kg (empty) a minimal friction of 0.21 is required. This leads to a measurement range of the friction coefficient at 100% traction of 0 – 0.21.

Choosing braking power handle

A driver can choose from 7 (operational) braking levels and the emergency brake. From braking level 1 through 7 the braking level increases proportionately for each measure. In the operational braking levels only the disc brakes and the ED brake are applied. All bogies except the motor bogie are equipped with disc brakes. All motor bogies can be used as an ED-brake. The difference between braking position 7 and the emergency brake is that with the emergency brake the magnetic track brakes are also be applied.



M: bogie with magnetic track brakes.

T: bogie with a traction installation/ED-brake.

Figure 5.4 Position in the train of the magnetic track brakes and traction installations.

At brake level 7 the VIRM experiences a deceleration of 1.39 m/s^2 (see reference [27]). If in the emergency brake position the magnetic track brakes are applied in addition to the disc brakes and the ED brakes the VIRM will experience a deceleration of 1,54 m/s^2. If a driver brakes with braking level 1, the train will experience a deceleration of 0.2 m/s^2 (is approximately 1/7 times 1.39 m/s^2).

The advantage of the ED brake compared to the disc brake is that it is less sensitive to abrasion and that energy can be transferred back to the overhead cable. In order to make better use of the ED brake, the coaches with an ED-brake use in braking levels (steps) 1 through 3 only de ED brake and not de disc brakes.

The measurement range at the various braking levels is shown in table 5.1. It must be noted that if slipping occurs when the brakes are applied the disc brakes will also be applied.

Braking position	Measurement range friction coefficient
1	0 – 0,04
2	0 – 0,08
3	0 – 0,12
4	0 – 0,14
5	0 – 0,14
6	0 – 0,14
7	0 – 0,14
8	0 – 0,14

Table 5.1 Measurement range friction coefficient dependant of braking position

Speed dependent

Figure 5.5 (retrieved from reference [28]) shows the tractive force characteristics of the three traction installations combined. It shows that the maximum force that the wheels can convey to the rail, by the motor, depends on the speed and the current of the overhead cable.

The horizontal part of the curve is a limited by software. It is meant to limit the maximum force that can be applied to the wheels. The reason is that if a large force is applied, the chance that a wheel will slip is significant.

The bent part of the curve is a limit caused by a maximum power. Due to a certain actual tension of the overhead cable the maximum power is limited. The effect on the measurement range μ_{max} is similar to that of the traction's characteristic.

When brakes are applied no dependency occurs between the force transmitted to the tracks and the overhead cable current or speed. The only thing that happens is that below a speed of 5 km/h the ED-brake is deactivated and it is not possible anymore to measure the friction coefficient. Braking only has an effect on the measurement range μ_{max} below 5 km/h

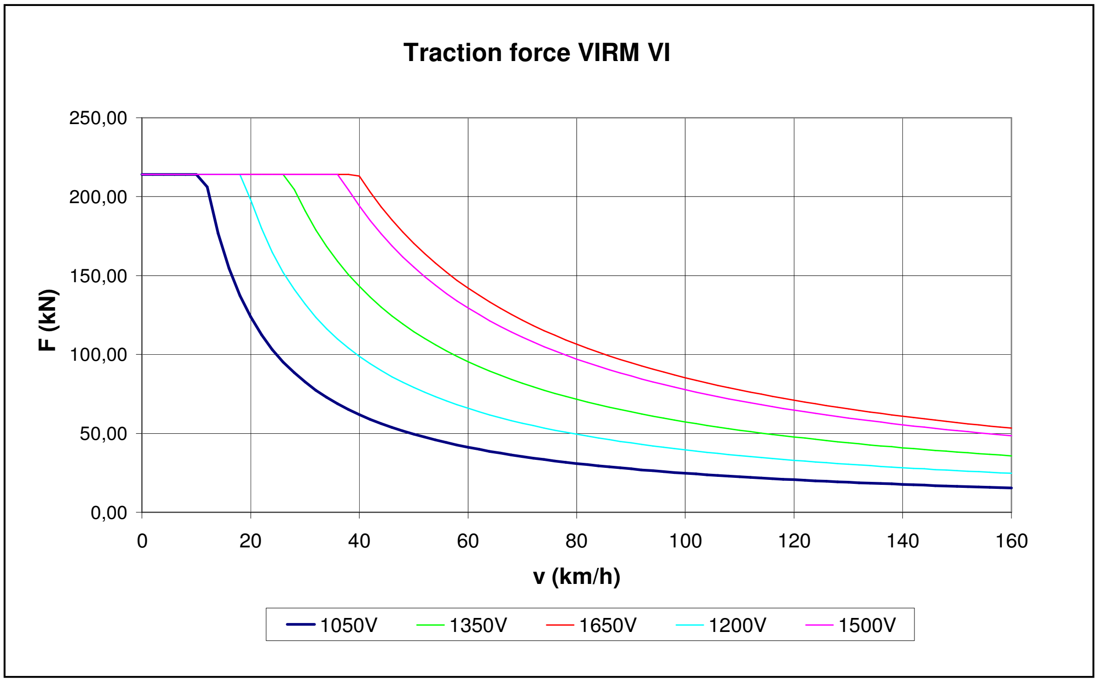


Figure 5.5 Traction force VIRM VI as a function of the speed for different tension of the overhead cable.

Conclusion

The measurement range of the VIRM tribo trains depends on the circumstances. For this research this does not pose a problem because the train's performance in everyday practice is investigated.

5.3.3 Functioning of the traction control and WSP when slipping occurs

The manufacturers of the traction control and WSP consider the control algorithms that have been made a trade secret. Therefore there is only a very limited amount of information available on the control algorithms of traction control and WSP in question.

If slipping (traction or braking) is detected, the applied motor torque is reduced gradually. It is not known which information from the traction control or WSP is used to make the decision to decrease motor torque and subsequently increase. In chapter 6 a proof of principle will be conducted with the VIRM tribo train. This proof will increase insight into the functioning of the control traction and WSP's line algorithm.

5.4 Accuracy

5.4.1 Determining the normal force (axle load)

The diagnosis system receives information from the pressure sensors in both air bellows regarding the load applied to the bogie. Based on this information the diagnosis system determines the axle load. The axle load is determined with an accuracy of 264 kg (see reference [29]). At an axle load of approximately 17.000 kg the accuracy is approximately 1,4%. This is an acceptable error.

5.4.2 Determining the motor torque

In Equation 5.2 is given how to calculate the tangential force on basis of the motor torque. The data of the motor torque is given by the traction control / WSP to the diagnosis system. The traction control / WSP calculates the momentary motor torque while this parameter is necessary for control of the traction installation / ED brake. According to the designers (Strukton Systems; formerly Holec) of the traction control / WSP is the motor torque determined with an accuracy of maximum 5 % (see reference [39]).

5.4.3 Neglect rotating mass

The motor torque serves as the basis for calculating the force on the wheel surface. A small part of the traction force is used to accelerate the rotating mass of the motors and the wheels. During a wheel slip this share will be larger because a strong increase of the wheel speed can occur.

No wheel slip
The total rotating mass of all axes in the train is approximately 3% of the train's total mass (345 tonnes and $I_{wielstel}$ is 100 $kgm^{2)}$. Of the 24 axes 6 have been equipped with a motor. These axes account for a quarter of the rotating mass (0.75%). The rotating mass also increases by the motors and gearboxes so the value of 0.75% is rounded at 1.0%.

Wheel slip
The tangential force is based on the motor torque see equation 5.3. In case of slip the acceleration of the wheel is much higher than if no slip occurs. Because of this big wheel acceleration dynamic forces become more important. A part of the motor force is used to accelerate/decelerate the wheel and not for traction/braking the train, the measurement system will show a higher friction value than there actually is. The following example shows that those dynamic forces don't lead to an unacceptable measuring error.

If a lot of wheel slipping occurs the mass inertia forces will be much higher than if the wheels do not slip. In case of maximum traction the torque on the wheel axle is 15.7 kNm. If in that case the tracks' friction equals 0 (most extreme case) the full traction torque will be used to accelerate the wheel. In case of a mass inertia moment of 100 kgm^2 for the wheels, the angular acceleration of the wheel will be 157 $rad/s^{2.}$ This is consistent with acceleration of the wheel surface of approximately 69 $m/s^{2.}$ In case of such a rapid acceleration the wheel will accelerate to a 15% slip in a fraction (<0.02s) of a moment. The fact that the angular acceleration is so high is caused by the high motor power compared to the relatively low mass inertia moment of the wheels and the low level of friction.

The WSP/traction control will therefore quickly reduce the traction/braking torque after slipping has occurred. In other words: the blue line in figure 5.3 will only relatively exceed the red one. The peaks in the curve of the blue line will come close to the red ones.

If the blue line surpasses the red line too much this will lead to extra abrasion of the wheels during traction and to flat spots during braking.

5.4.4 Wheel radius

Equation 5.3, which includes the wheels diameter, it has not been taken into account that the wheel's diameter can vary due to the fact that the wheel diameter decreases by turning the wheel during maintenance. The wheel's diameter can very between 840 and 920 mm. In equation 5.3 an average value of 880 mm is used for the calculation. If the diameter is either the minimum or maximum size, a maximum error will occur. This is 40/880 mm, which is 4.5%.

The motor current on which the motor torque is based can be determined with great accuracy. Compared to other effects on the accuracy mentioned in this paragraph, the effect of the motor current on the total measuring error is minor.

5.4.5 Line algorithms traction control and WSP

Figure 5.6 depicts the same slippery situation showed in figure 5.3 with this difference that the traction control/WSP response to low adhesion is not the same. It takes longer to notice that the friction has changed. In addition, the system mentioned in figure 5.6 takes longer to adjust the braking/traction torque. Therefore only two points can be used to determine low adhesion. The consequence hereof is that, based on the system mentioned in figure 5.6, it is more difficult to obtain insight into the progress of the friction coefficient μ_{max}.

As previously stated, due to the fact that we are dealing with a trade secret, there is not much information available on the VIRM control algorithms of traction control and WSP. Therefore no insight can be obtained into the accuracy that is feasible by using the system mentioned as a measurement tool for adhesion. Insight into accuracy must be determined by a proof of principle.

It must be noted that a train equipped with traction control/WSP that operates as displayed in figure 5.6, suffers more from low adhesion than a system that operates in accordance with figure 5.4. The traction/braking torque in figure 5.6 is reduced to a needless extent, which has serious consequences on the traction and braking performance.

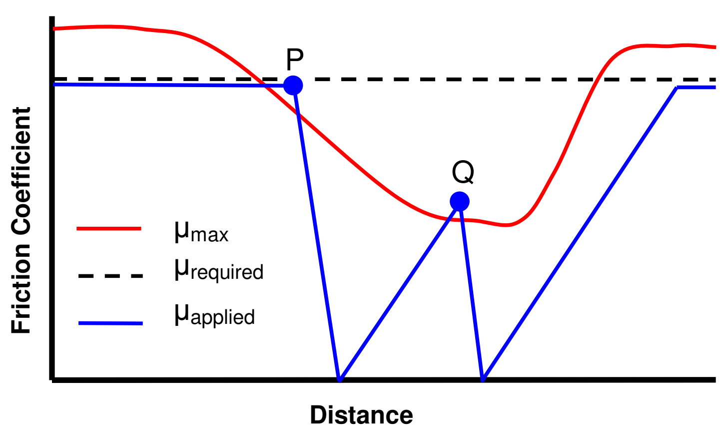


Figure 5.6 Friction coefficient as a function of the distance.

5.5 Conclusions

Based on the preliminary research conducted in chapter 5, it has been proven that the concept of the VRIM tribo train in theory is suitable to measure the extent of low adhesion. Based on this preliminary research poor general insight into the accuracy of the measurement system has been obtained. From the aforementioned analysis regarding accuracy it has not been proven that measuring by this method is impossible. A proof of principle (see chapter 6) will have to show whether this measurement system actually operates in practice as is thought and will have to answer the question of accuracy.

Should the proof of principle show that the invented measurement system's accuracy is not as high as expected it will at the very least be possible to obtain insight into how much the train suffers from low adhesion.

Remark
The difficulty in utilizing the information derived from the diagnosis system is that it requires a lot of knowledge about various train systems.

6 Proof of principle

In order to determine whether the VIRM's traction installation/ED brake is in fact suitable to measure the friction coefficient, theoretical research has been conducted to find out if this is in fact possible (see chapter 5). The next step is to discover if the devised idea actually works in practice; this will be done by a proof of principle. This paragraph will describe the test.

6.1 The purpose for the test

The purpose for the test is to determine whether it is possible to measure low adhesion from a VIRM train with the method described in chapter 5. It also needs to be determined how accurate the measurement system is and the minimum sample frequency that is required.

Determining accuracy

The accuracy of the recorded adhesion can best be tested by determining what the friction coefficient is for track (test track) that have been artificially made slippery and to compare that value with the results from the VIRM tribo train. However a measurement system that can accurately determine the friction coefficient of the track was not available for this test.

In order to ensure that accuracy can actually be obtained, a test course is artificially made slippery over a distance of approximately 200 meters. Subsequently the test train (VIRM tribo train) measures the adhesion during traction as well as during braking. The accuracy of the measurement is assessed with the hand-pushed-tribo meter (see §4.4) and by determining the adhesion based on the braking deceleration/traction acceleration distances (see §4.1).

The control algorithm of traction control WSP

Suitability of the traction control/WSP's control algorithm to determine the friction coefficient is assessed based on the path of the motor torque (proportional with tangential force) on tracks that have artificially been made slippery.

6.2 Test set-up

This paragraph describes the test set-up.

Test location

Tests were conducted on tracks 505 and 512 at the train yards in Onnen, south of the city of Groningen. The tests were conducted on February 2, 2007. However, at train yards the maximum speed is 40 km/h. At the start of the test a lot of rust was visible on the track rails of the test route, the surface was not visible, see figure 6.1.

Figure 6.1 Rust on the rail

Test train

The train used to conduct the tests is a six wagon train from the first series, wagon number 8624 (see figure 6.2), supposing that the test train has wheels with an average diameter of 840 mm.

Figure 6.2 VIRM train.

Required measurement information

In order to determine whether it is possible to measure adhesion with the method mentioned in chapter 5, information regarding the occurrence of slipping and the applied breaking/traction torque must at least be available. As the test is conducted with an empty train the axle load (normal force) does not need to be determined, because the axle load of an empty train is a given.

To determine the average friction coefficient of the tracks artificially made slippery §4.1 suggests it is necessary to know what the momentary speed is so that the braking deceleration/traction acceleration can be determined. For this test the information regarding motor torque, occurrence of wheel slip and speed are instantly read out from the traction control/WSP by using a laptop; thus not from the diagnosis system.

Each motor bogie has its own control. In order to keep the test simple the information of just one motor bogie (of the three) was read out. The advantage of reading out from the traction control/WSP is that the sample frequency is 10 Hz instead of 1Hz if the same information is read out from the diagnosis system.

Even though it is not necessary for the test the torque applied by the driver is also read out.

Measurement instruments used
Laptop for measurements
By using a laptop and Wincomm software the required parameters are read out of the traction control/WSP of the chosen bogie. Read out can be done simply by connecting the laptop with a cable to the computer of the traction installation/ED-Brake's control.

Hand-pushed-tribometer
The only simple method available for obtaining insight into the tracks' friction is the hand-pushed-tribo meter. This measurement tool offers only general insight into the extent of adhesion. This measurement tool is used for lack of a better system. Prior and after each test, measurements using the hand-pushed-tribo meter were conducted.

Friction reducing agent
With the help of the VIRM tribo train method the friction coefficient can only be measured if slipping (during braking or traction) occurs. In order to create this specific situation adhesion must be reduced. Adhesion is reduced by applying grease (Kajo Bio) to the rail and/or on the wheel, see figure 6.3. The grease used is Kajo Bio. The anticipated friction coefficient is 0.02.

Figure 6.3 Applying grease to the rails in order to make the track slippery.

6.3 Conducted tests

Only the tests with results that provide the most insight are discussed in this paragraph. In reality the test program was more extensive. In order to obtain insight into the accuracy and functionality of the line algorithm various tests were conducted:

1. Tests during traction and braking.
2. Tests on dry track.
3. Tests where the tracks were made slippery with grease.
4. Tests where bogies were de-activated.

6.3.1 Insight into the control algorithm

This paragraph describes how the traction control/WSP adjusts motor torque during low adhesion. The results of 3 tests are described below.

Test Number 1

During the first test slip occurred during acceleration straight away. The slipping was probably caused by the fact that the tracks were rusty and somewhat moist/damp. In figure 6.4 the yellow line shows the forward force applied by the driver in comparison with time. The green line shows the actual forward force of one wheel set on the rail. The red line shows the wheel's peripheral velocity ($\omega \times r$). The peaks in the velocity's curve indicate that the wheels' velocity increases disproportionally, which indicates that the wheels are slipping. It shows that within fractions of a second after slipping occurs, the traction installation reduces motor torque.

Figure 6.4 also shows that it takes approximately 1 to 2 seconds after slipping occurs for the peripheral velocity of the wheel to be equal to that of the train. In order to allow the wheel to obtain the peripheral velocity as quickly as possible the motor torque is reduced to 0, which leads to the forward force of one wheel set on the rail (green line) to be reduced to 0 also. If after slipping the peripheral velocity once again equals the train speed, the motor torque is gradually increased. As is shown, this cycle takes approximately 8 seconds. It is also shown that the traction torque is increased in two steps. The yellow line shows the forward force desired by the driver.

Figure 6.4 Tangential (traction) force of the wheel on the rail as a function of time and peripheral speed of the wheel as a function of time.

As indicated in §3.1, based on the forward force applied by a wheel set on the rails and the normal force (axle load), the friction coefficient can be determined. As the test train is empty the axle load equals the axle load of an empty train. The forward force is thus known (green line in figure 6.4).

The orange line shows which adhesion is required to apply the force desired by the driver via the wheels to the rails. The calculated friction coefficient is depicted in figure 6.5 as a function of time (blue line). After wheel slip has occurred the maximum measured friction coefficient is approximately 0.15. In the next paragraph the accuracy of this measurement will be discussed in further detail. The pink line shows the average calculated friction coefficient, from the moment that the wheel starts to slip until the moment that the driver has reduced the force applied to 0 kN.

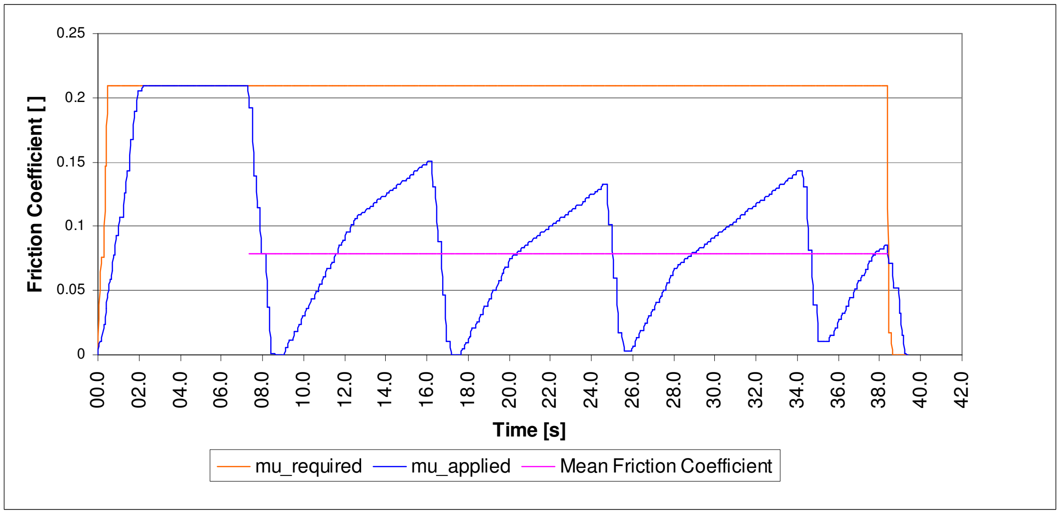


Figure 6.5 Friction coefficient as a function of time.

Test Number 2

During test number 2 only one of the three driven bogies was activated. The tracks and the wheels were made slippery with grease. The obtained control signal under these circumstances is shown in figure 6.6. Even though it is extremely slippery and only one traction installation is activated, the train still moves. Figure 6.6 shows that the tangential force to the wheel surface is constantly brought back to 0 kN after each slip (green line). In figure 6.6 there are three instances where a wait of approximately 0.5 s was applied before increasing traction torque. In this test also traction torque is increased in two steps. For this test the cycle lasted between approximately 1 s and approximately 8 s.

The corresponding calculated curve of the friction coefficient is depicted in figure 6.7 (blue line). The peaks of the friction appear at approximately 0.05. The pink line shows the average calculated friction.

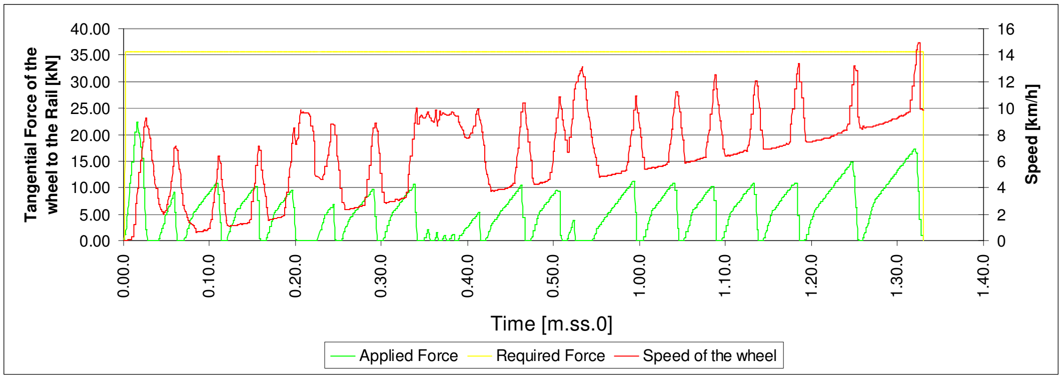


Figure 6.6 Tangential (traction) force of the wheel on the rail as a function of time and peripheral speed of the wheel as a function of time.

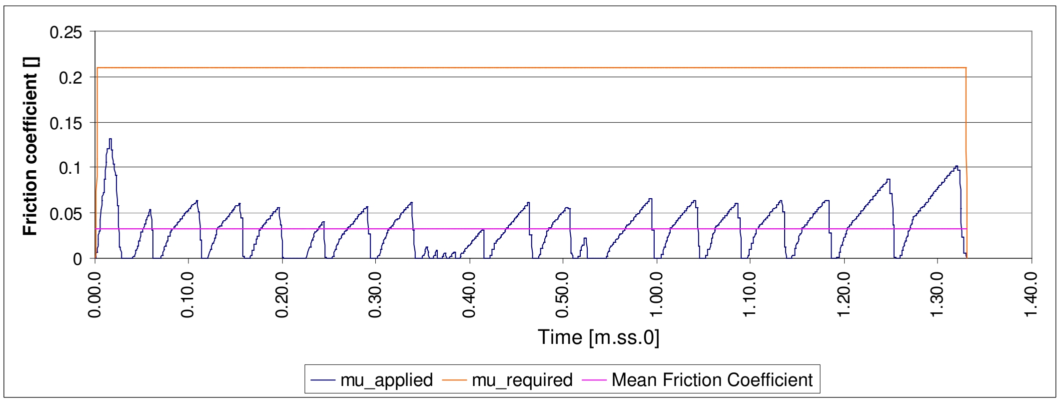


Figure 6.7 Friction coefficient as a function of time.

Test Number 3

No test results were obtained for situations where braking occurred on tracks that were so slippery that slipping occurred, but were not so slippery as after grease had been applied. Therefore it cannot be shown how the control technique responds to a medium friction level. Below in figure 6.8 it is shown how the WSP reacts on tracks that have been made slippery with grease.

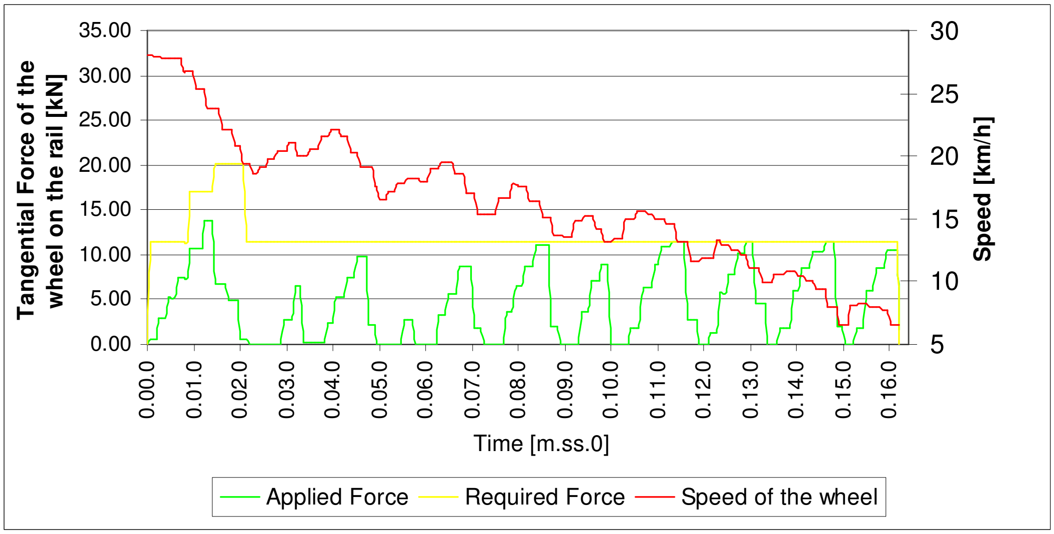


Figure 6.8 Tangential (braking) force of the wheel on the rail as a function of time and peripheral speed of the wheel as a function of time.

The red line in figure 6.8 shows the wheels peripheral velocity. The yellow line shows the forward force required by the driver from the wheel to the rail. The green line shows the actual applied force from the wheels to the rail by the ED-brake. A cycle during braking takes approximately 1.5 s. If figures 6.6 and 6.8 are compared it stands out that the cycle which is increased to reach the same force on the wheel surface during braking is approximately 3 times shorter than during acceleration. The corresponding calculated friction coefficients are depicted in figure 6.9. the peaks in this figure run van 0.018 to 0.08.

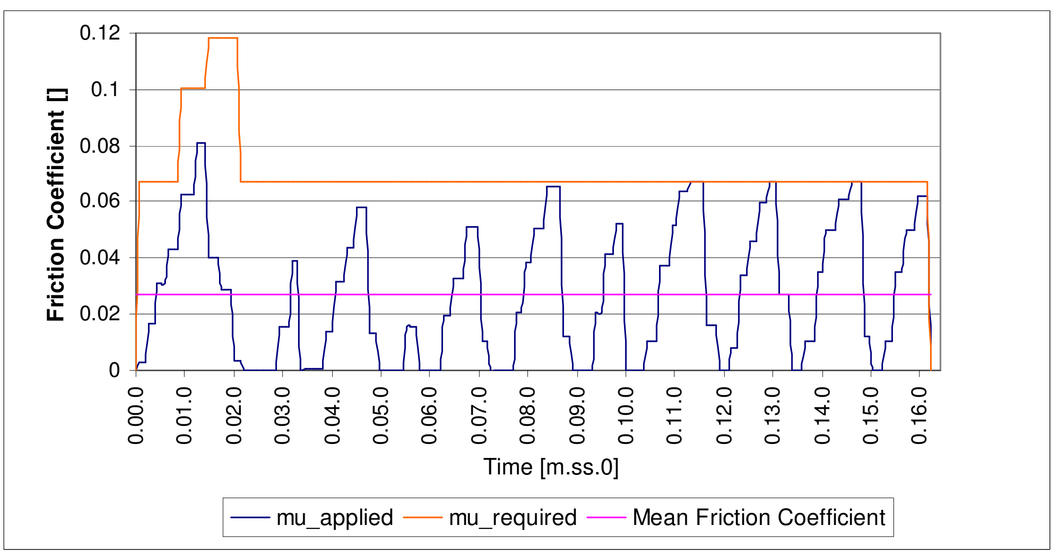


Figure 6.9 Friction coefficient as a function of time.

Observations and interpretations

When slipping occurs the traction control/WSP adjusts the motor torque to 0 Nm after which torque is again increased. It was observed that torque was increased in two steps. The measurement system clearly shows a difference between slippery (rusty) tracks and extremely slippery (greasy) tracks. The curves achieved in this paragraph look more like the ones in figure 5.6 than the ones in figure 5.3.

The average of the measured friction coefficients (pink line) is much lower than the peaks in the friction curve supplied. This is caused mainly because after slipping, it takes a long time for the peripheral speed to get back to the same level as the speed of the train and because increasing motor/ED-braking torque takes a long time. If a driver chooses a traction/braking level that requires a friction that lies between the pink line and the peaks in the supplied friction, then higher braking deceleration/traction acceleration can be obtained than if a traction/braking level is chosen that is in accordance with the yellow line. In other words, if the driver operates correctly that could lead to an improvement of performance.

Therefore it is pointless to obtain information from the traction control/WSP with a higher sample frequency of 10 Hz. The biggest problem why a cycle takes so long is due to the fact that it takes a long time before a slipping wheel has achieved a peripheral velocity that equals the train's speed (see figures 6.4, 6.6 and 6.8). This is caused by the bogie and gearbox' high level of mass inertia in comparison to the low level of adhesion between wheel and rail. Possibilities for increasing efficiency of the WSP/traction control are:

1. Intervene during a lower slipping percentage. As mentioned, it takes long after slipping is detected for the peripheral velocity to get back to an equal level of the forward velocity (this is mainly true for the traction installation). By intervening at a lower slipping percentage the maximum peripheral velocity that will occur will be lower and the peripheral velocity of the wheel will equal the forward speed quicker. This will result in the traction/braking force to be reduced for a shorter period of time.
2. Braking while the wheel is slipping during acceleration and accelerating while the wheel is slipping during braking until the peripheral velocity and train speed are equal. This will result in a reduction of the time required for traction/braking force to be reduced.
3. Making control smarter by:
    a. Using the measurement information from other wheels in the train.
    b. Processing the slipping history to predict maximum motor/ED braking torque applied.
    c. The time required after slipping, before the peripheral velocity is equal to the train speed, is a indicator for the tracks' adhesion. This information could be used to determine the optimal motor/ED-braking torque on a slippery rail.

6.3.2 Insight into the accuracy of the VIRM tribotrein

The accuracy of the VIRM tribo train proved to be much higher than the accuracy of the hand-pushed-tribo meter. Therefore the hand-pushed-tribo meter cannot offer insight into the accuracy of the VIRM tribo train. As previously mentioned in §4.1 the average adhesion value over a certain course can also be determined by establishing the deceleration/acceleration over that same course. In order to obtain sufficient insight into the accuracy it is necessary that:

1. The course is long enough to determine the acceleration/deceleration accurately enough.
2. The friction along the test course is constant so that all wheels for which the brakes are applied or accelerated experience the same adhesion.
3. In case the brakes are applied to ensure that only the ED-brake is used.

During the execution of the test these requirements were not yet clearly envisioned. Therefore, not all tests are suitable to offer insight into the accuracy of the VIRM tribo trains. As such none of the braking tests are suitable to establish the accuracy of the VIRM tribo train because none of the tests were conducted only using the ED-brake. During all braking tests the disc brakes were also applied. If the possibly incorrect assumption is made that the effectiveness of the disc brakes on a slippery rail is exactly the same as the effectiveness of the ED-brakes than it is possible to obtain insight into the accuracy of the VIRM train during braking.

If for tests 1, 2 and 3 the average acceleration/deceleration and therefore the friction coefficient can be determined, the values as shown in table 6.1 (column 2) will be obtained. In figures 6.5 and 6.7 and 6.9 the average measured friction coefficients are shown with a pink line. These values are also depicted in table 6.1 (column 3).

	Determining µ based on average deceleration/acceleration	Determining µ based on average friction µ measured
Test 1	0,079	0,078
Test 2	0,031	0,032
Test 3	0,038	0,027

Table 6.1

If the values in column 2 and 3 of table 6.1 are compared to each other it stands out that the values during test number 1 and 2 (traction) are almost equal in both columns. The difference between column 2 and 3 is larger for test number 3 (braking). An explanation for this could be that the disc brakes contribute more to the braking deceleration than the ED-brakes do. Another possible explanation for this is that more tracks are roughened because brakes are applied to all axes.

Conclusion

Based on the fact that the average friction values measured by the VIRM tribo train for acceleration are almost equal to the calculated friction value, it can be concluded that based on the measured motor torque the tangential force, which is applied by the wheels to the rails can be determined accurately.

The maximum adhesion that can be utilized is the adhesion that is recorded just before a peak is reached. After all, when the peak is reached the friction present will be just under the required level and slipping will occur. Because it has been shown that the tangential force can be determined accurately it is plausible that the peaks in the curve that shows the tangential force (green line) can be determined accurately. The tangential force's curve has the same shape as the curve of the utilized adhesion (blue line). The peaks in the curve of the utilized adhesion therefore will also be able to be determined accurately.

6.4 Conclusions and recommendations

Based on the executed proof of principle it has been proven that it is possible to determine the extent of adhesion by using the VIRM tribo train. The VIRM tribo train is therefore suited for the application envisioned.

The impression has arisen that mainly the traction control and to a less extent the WSP leaves room for improvement. This improvement should lead to a better utilization of the adhesion present and therefore to an improvement of the traction performance.

The traction control is insufficient on slippery track to such an extent that it cannot be ruled out that if the driver's operation is optimal; the traction performance will outperform that of the traction control.

7 Answering the research questions

This chapter will answer the research questions mentioned in chapter 1 based on the measurement information obtained. In order to obtain the required insight, the measurement information has been processed by analyzing methods (algorithms) developed specifically for this purpose. This chapter has two goals. This research must ascertain whether or not the measurement method developed offers insight into the various research questions. If so, it also attempts to answer the research question concerned. Possibly it will be ascertained that certain answers can be found but that to do so requires that the testing method be improved.

7.1 Deploying measuring trains in practice

This paragraph describes the choice for the final design of the VIRM tribotrain for deployment in practice. It also will describe how the test was set up.

7.1.1 Choice for the measuring train(s)

Tests in practice on the railways are expensive. Therefore it is impossible to develop an ideal measurement set up. Considering the limited budget two options remain:

Developing one VIRM tribo train that will supply the required information from one traction installation/ED brake on slipping [yes/no], applied traction/braking torque, required traction/braking torque, axle load, velocity and the train's location with a sample frequency of 10 Hz.

Developing five VIRM tribo trains that will supply the required information for all three traction installations/ED brakes on slipping [yes/no], applied traction/braking torque, required traction/braking torque, axle load, velocity and the train's location as well as the number of the coupled train, driving direction, activated magnetic track brakes. The sample frequency for this set up is only 1 Hz. The reason that this set up is relatively inexpensive is because for the most part an existing measurement set up can be used.

The second option was chosen. The reason for this is that §5.1 states the importance to conduct a large number of measurements over a certain section (trajectory). 5 measuring trains enable more measurements to be conducted. The disadvantage is that it is less accurate. The total measurement system that the 5 VIRM tribo trains are a part of, functions in accordance with the configuration, depicted in chapter 5.

Developed measurement systems prove not to meet the specifications
When the first results of the 5 VIRM tribo trains that were running in service were analysed, it was established that the sample frequency was not constant. If the diagnosis system needed to supply too much information, a prioritization in the system ensured that the sample frequency to the PMMS box was reduced, in some instances as low as 1/7 Hz. The choice was made to reduce the sample time consistently to 1/3 Hz. Therefore, no variations in sample time occurred, from then on.

For the test envisioned, a sample frequency of 1 Hz was considered a bit too low. A sample frequency of just 1/3 Hz unfortunately reduced the level of accuracy even more. The low sample frequency of 1/3 Hz was somewhat compensated by the fact that the three separate traction installations/ED-brakes measured the same part of the tracks. In fact, this is in itself a form of increased sample frequency. Only the distance between the samples during a certain speed can differ.

7.1.2 Test set up: tribo trains in service

In order to be able to answer the research questions, in §5.1 are not only for the measurement sytem requirements and desires stipulated, but also for the measuring set up (the test set up). This paragraph will show how the different demands and wishes for the set up were met.

Monitoring in the fall and during other seasons
In order to be able to investigate to what extent low adhesion is a problem during the fall season it is necessary to conduct measurements during the fall as well as during a reference period in another season. Therefore measurements were conducted from June 30, 2008 through January 30, 2009.

Monitoring one section
In order to ensure that a relatively large number of measurements during the fall were available from a limited number of stations, the 5 VIRM tribo trains were deployed on a fixed section. The section Den Helder – Nijmegen (Series 3000) was chosen. The reason for this choice is: it includes a smooth section (Arnhem – Utrecht). Another reason to choose the 3000 Series is that it stops regularly, depending on the time of day between 17 and 20 times. This boils down to approximately 1 stop every 10 minutes. In fact, the 3000 Series is for the most part a local train. Because it stops and accelerates frequently, the chance of slipping wheels is significant which is interesting for the research.

Deployment on a fixed section only took place during the fall, because it requires a significant effort from NS to keep the trains in circulation. From October 6, 2008 through December 13, 2008 the measuring trains were deployed as much as possible on this section. From Monday through Friday 2 trains started in Nijmegen and 3 in Den Helder. On Saturday 2 started in Nijmegen, 2 in Den Helder and 1 in Alkmaar. And on Sundays 1 started in Den Helder and 3 in Nijmegen and 1 was out of service. Subsequently the VIRM tribo trains continued to ride on this section all day.

Importance of storing information about situations when slipping does not occur
In order to make a proper analysis, it is important that not just the information regarding cases of low adhesion are saved but that all moments that no slipping occurs are also stored. In that case insight can be obtained into what is normal and what can be considered as incidents.

7.1.3 Required algorithms

Algorithm to determine friction
As mentioned above, the sample frequency for the developed test trains (VIRM tribo trains) was much lower than intended. Due to the low sample frequency it is not possible to determine the peaks in the friction curve (see figures 6.4, 6.6 and 6.8). This was an elegant aspect of this method. In order to compensate for the problem an alternative was found. In general, the alternative was to determine the low adhesion based on the average of a number of friction samples (comparable to the pink line in figure 6.4, 6.6. and 6.8).

By determining the average friction coefficient of the friction curve instead of the peaks, accuracy diminishes, which is unfortunate. On the other hand, the alternative shows not only how slippery the tracks are, but also how effective the trains handled the low adhesion at hand.

If it is very slippery and the traction control/WSP postpones the power increase, that is accounted for in the friction coefficient. This alternative method is explained below in further detail.

Events
Events must be stipulated in order to be able to obtain insight into low adhesion. An event is a collection of consecutive samples in which at least on traction/ED braking system slips. If in x + n slipping occurs, it is only considered as the same event as sample x, where slipping also occurred, if it occurred no more than 1 minute before.

Gravity of an event
A standard was determined that indicates to what extent a train is inconvenienced by an event. This standard is referred to as gravity. As gravity increases, the inconvenience that a train suffers from low adhesion increases. The following has been taken into account for the standard:

1. The level of low adhesion during the event.
2. Duration of the event.
3. The number of systems that slip.

The calculation is as follows:

$$Gravity = \sum_{t=last\ sample\ event}^{t=first\ sample\ event} \frac{slip_{1,t}}{\mu_{1,t}} + \frac{slip_{2,t}}{\mu_{2,t}} + \frac{slip_{7,t}}{\mu_{7,t}} \qquad \text{Equation 7.1}$$

The slipping values in this equation are 1 or 0 depending on whether or not traction installation/ED brake 1, 2 or 7 slip. If slipping occurs μ_1, μ_2 en μ_7 are the friction values measured by the traction/ED braking system for respectively cabin coach 1, cabin coach 2 and middle coach 7.

Classification of the gravity value
This paragraph shows what the minimum value for the gravity has to be in order for it to contribute to a substantial reduction of driving on time percentage (punctuality) and reduction of safety. On the other hand, considering it is an abstract parameter, this paragraph will also offer a sense of what the parameter gravity is.

<u>Minimal gravity</u>
Low adhesion with limited gravity is not a problem for railroad traffic. It merely has a limited effect on the braking distance or acceleration length and therefore only has limited consequences on safety, driving time, driving on time percentage (punctuality) and capacity. Due to their limited influence, events with an effect smaller than 500 are not taken into consideration. The effect of an event with a gravity level over 500 is similar to three traction installations/ED brakes that measure adhesion during 5 samples (15 s) of μ=0.03; or 1 traction installation/ED brake that for a period of 15 s measures a friction of μ=0.01. If the friction coefficient is μ=0.01, the train is barely capable of transmitting any force whatsoever to the tracks (approximately 5% of maximum force).

If the level of gravity is smaller or equal to 500 during braking or acceleration it still meets the minimal requirements for braking (safety) and traction performance (driving time, driving on time punctuality).

7.1.4 Rough measurement date (compounded data table)

In order to be able to answer the research questions, chapter 5 states which parameters need to be monitored. In the columns, table 7.1 shows which ones are concerned. In this table the diagnosis system supplied the information in yellow and the green information comes from the GPS.

Sample nummer	Matnr	DateNum	Tact1	Tact2	Tact7	Load1	Load2	Load7	Slip1	Slip2	Slip7	V	Treq1	Tre21	Treq7	Rem1	Rem2	Rem4	Snelrem	MGrem1	MGrem2	ATBrem1	ATBrem2	numberT1	numberT2	md1	md7	md2	GPSlat	GPSlong
1																														
2																														
3																														

Tabel 7.1 Structure slipping database with measurement information.

Here:

Matnr	VIRM Tribo train Train number (8636, 8640, 8642, 8654 0f 8666).
DateNum	Date and time of the sample.
Tact	Applied motor torque (braking or traction).
Load	Axle load.
Slip	Shows whether the motor bogie concerned experiences slipping [yes/no].
v	Velocity.
Treq	Is the required traction/braking torque by the traction control/WSP applied to the motor bogies; because of the priority arrangement this value does not need to equal the braking torque (braking level) required by the driver.
Rem1, Rem 2 and Rem4	Displays a binary code indicating the braking level chosen by the driver.
MgRem	magnetic track brake in cabin coach 1 or 2 activated.
NumberT	Displays the number of the multiple unit in the total train.
Md	Displays which bogie in the train slips.
GPSlat and GPSlong	GPS coordinates.

A number of columns will be added to this table by using algorithms. To start with that will be the calculated friction coefficient of, in succession, bogies 1, 2 and 7. These columns are called Adhesion 1, Adhesion 2 and Adhesion 7. Subsequently the samples that are part of one event are assigned the same serial number; column piece.

Subsequently, the gravity for each line is established. That column is referred to as ‘slip indication’. That value is obtained by filling in the values concerned in equation 7.1 (without the summation symbol) for adhesion 1, adhesion 2 and adhesion 7 plus the values of slip 1, slip 2 and slip 7. Finally, the gravity for each event (with the same piece number) is determined by means of equation 1. These values are listed in the SEI (slip event indication) column.

Table 7.2 shows all data; both the measured (yellow and green) as well as the calculated (blue) values.

Sample nummer	Matnr	DateNum	Tact1	Tact2	Tact7	Load1	Load2	Load7	Slip1	Slip2	Slip7	V	Treq1	Tre21	Treq7	Rem1	Rem2	Rem4	Snelrem	MGrem1	MGrem2	ATBrem1	ATBrem2	numberT1	numberT2	md1	md7	md2	GPSlat	GPSlong	Adhesion1	Adhesion2	Adhesion7	Piece	Slip Indication	SEI
1																																				
2																																				
3																																				

Tabel 7.2 Structure slipping database including measured (yellow and green) and calculated data (blue).

7.2 Basic information to answer research questions

This paragraph shows two methods used to report data, which is used in various paragraphs in this chapter. These are the time-distance-diagrams for a certain location and the maps that indicate where low adhesion has occurred.

7.2.1 Maps that show where low adhesion has occurred

In order to obtain insight into where low adhesion has occurred, maps of the Netherlands have been charted which show the various events with a gravity level of over 500 (see §7.1). An example of this can be found in figure 7.1. A colour code is used to indicate the gravity of the event; blue stands for a low level of gravity and red for a high level.

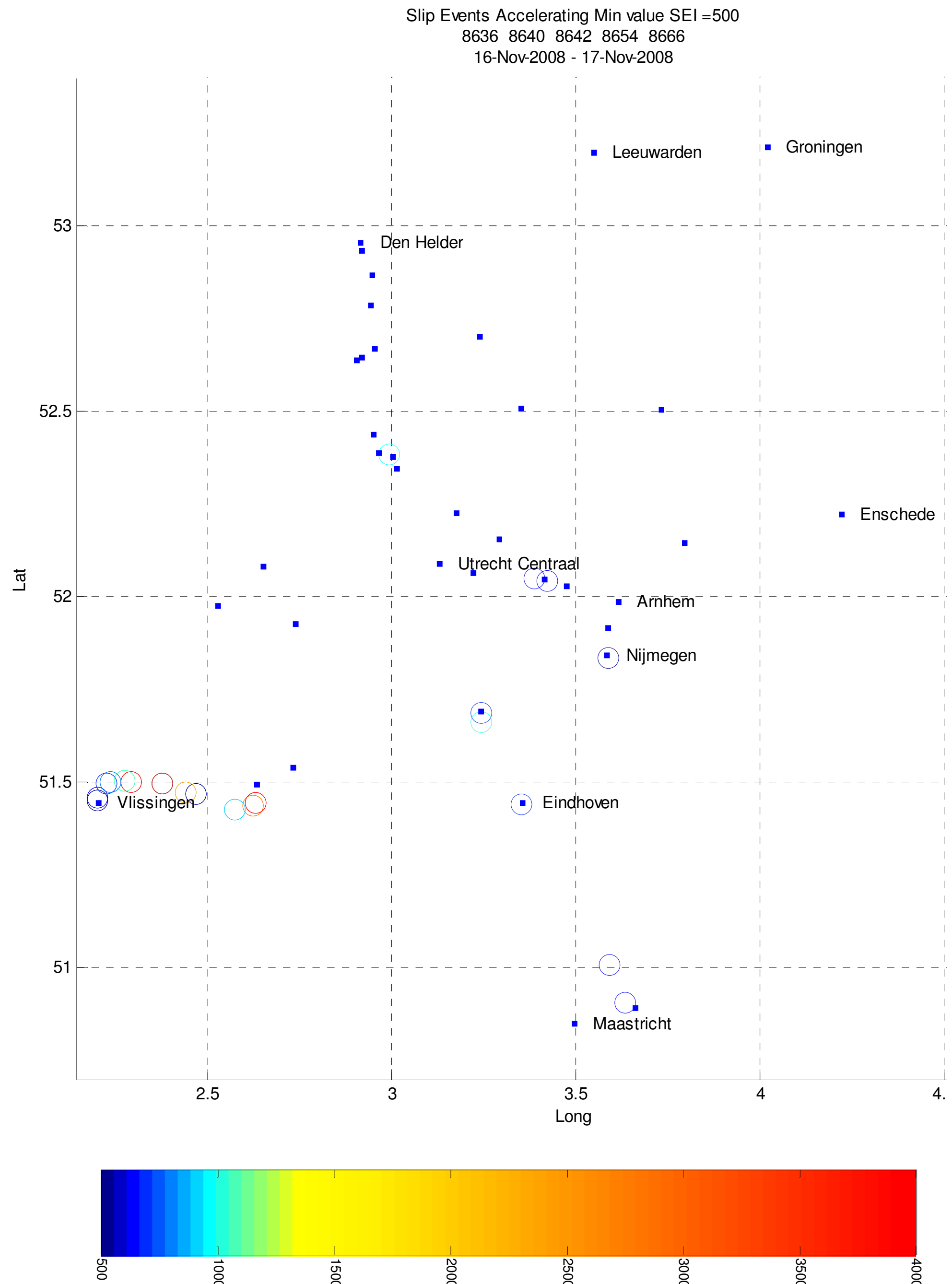


Figure 7.1 Low adhesion on November 16, 2008.

7.2.2 Time-distance diagrams

In order to obtain insight into the effect of a measure at a certain location or to obtain insight into how low adhesion can change in time during a day, time-distance-diagrams of areas around stations have been made. Figure 7.2 shows an example of a time-distance-diagram. In a time-distance-diagram the route that the VIRM tribo trains have travelled is plotted against the time. The horizontal axis shows the location and the vertical axis shows the time. In the chart the route travelled is shown as a blue or black line. This was done in order to make a distinction in the direction that the train was driving.

For the various researches it is paramount to know where slipping of the motor bogies has occurred, where Sandite was applied and whether the train stopped at the station in question. Whether the driver stopped can be concluded from the fact whether the driver applied the brakes or if the driver applied over 50% traction.

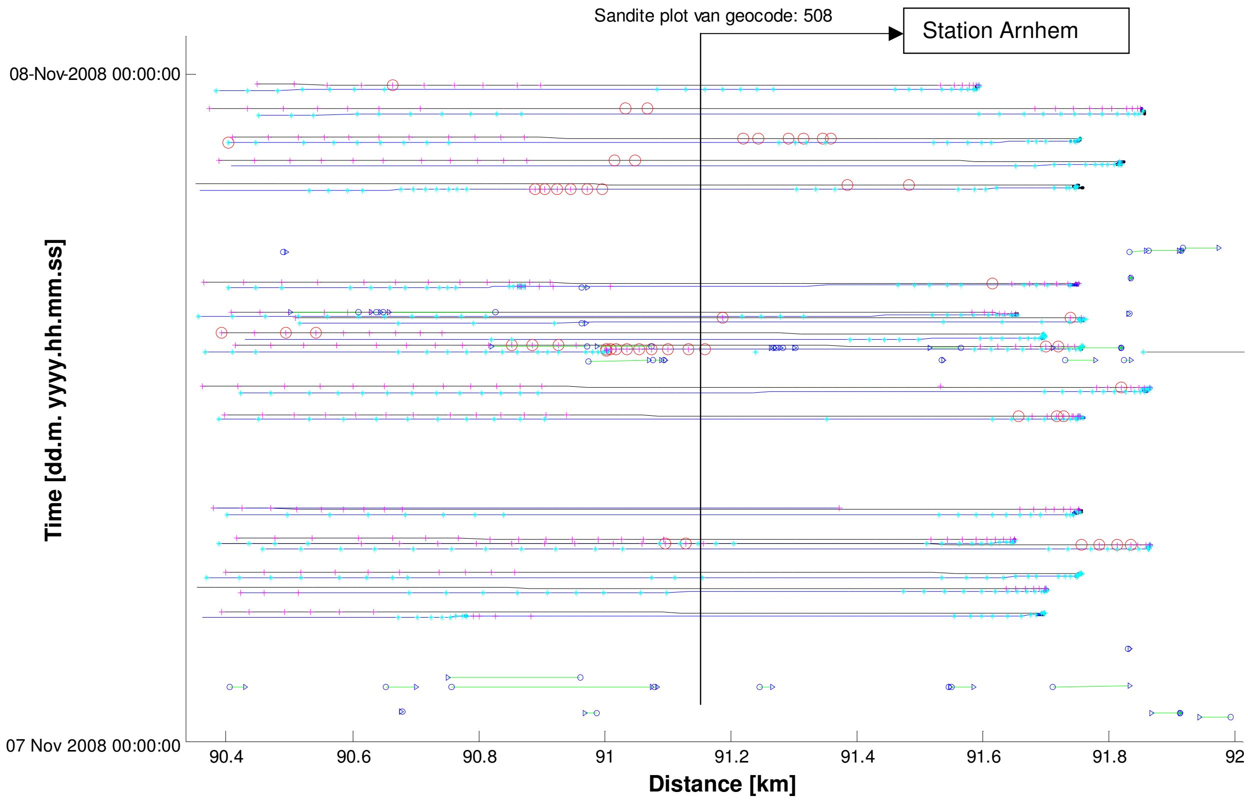


Figure 7.2 Time-distance-diagram for Arnhem station on November 7, 2008.

Below chart displays what the various symbols used stand for:

A black line shows a measuring train that is driving to the left.

A blue line shows a measuring train that is driving to the right.


A red circle shows that the measuring train slipped at this location for 3 s.

The light blue star shows that a the driver in a measuring train applied the brakes.


A red cross shows that the driver applied over 50% traction.

A light green line shows that Sandite was applied. A blue circle shows where it was applied first and a blue triangle shows where application was discontinued. Based on this information it can be established whether Sandite was applied on a forward or return railroad section.

Remark:
NS deployed the five VIRM tribo trains in such a way that during the fall season they mainly drove between Den Helder and Nijmegen. Therefore the measuring trains might have passed the various stations on the section multiple times a day, which offers insight into the development of low adhesion during the day.

7.3 Current braking system's performance in case of low adhesion

This paragraph investigates how often a train ended up in a possibly dangerous situation during a situation with low adhesion. This answers research question number 2.

7.3.1 Braking levels used

Based on the obtained measurement data from the VIRM tribo trains, it was ascertained that the drivers generally only apply low braking levels. The braking levels are divided as depicted in table 7.3. It must be noted that the percentage for the emergency brake is not reliable.

Braking level	1	2	3	4	5	6	7	Emergency brake
Percentage of use [%]	56,6	31,4	8,6	1,9	0,3	0,1	0,1	0,9

Table 7.3 Percentage of use of the different braking levels.

The braking deceleration for braking levels 1, 2 and 3 are respectively 0.2, 0.4 and 0.6 m/s^2 (see reference [27]). For this an average friction coefficient (μ) of respectively 0.02, 0.04 and 0.06 is required on the track, the with percentage of use weighed average friction coefficient is: μ = 0.032. This is a low friction coefficient, which indicates that, on average, this friction coefficient will (nearly) always be present in the part where braking takes place. The fact that the required friction coefficient is almost always present explains why red-signal passages due to low adhesion occur relatively infrequent.

7.3.2 Required braking distance

In the regulation railway traffic chapter 3, §1, article 8 (http://wetten.overheid.nl) shows that a train must be equipped in such a way that for a velocity of 140 km/h (maximum velocity in The Netherlands) the braking distance must be at the most 1150 meters. This results in a minimum friction coefficient along the braking distance of μ = 0.066.

7.3.3 Red-signal-passages with VIRM tribo trains

From 1999 through 2005, 2192 red-signal-passages occurred in The Netherlands (information supplied by IVW – inspection for traffic and public works, see also paragraph 2.2.1). Of these, 128 are were partly or fully due to low adhesion. Of these 128, 3 occurred with VIRM. Characteristics for these 3 excesses are:

Red-signal-passage 1: Passenger train stopped somewhere between 0 to 25 meter past the red signal in which case a possible dangerous point was reached. How the driver operated did not contribute to the red-signal-passage happening.

Red-Signal-passage 2: Passenger train stopped somewhere between 0 and 25 meters past the red signal but a possibly dangerous point was not reached. How the driver operated did contribute to the red-signal passage happening.

Red-Signal-passage 3: Empty passenger train stopped over 100 m past the red signal but a possible dangerous situation did not occur. How the driver operated contributed to the the red-signal-passage happening. The driver noticed the red signal too late.

This information shows that not just the first occurrence can be put down to low adhesion. To which extent situation 2 and 3 can be put down to low adhesion is not clear because the driver's incorrect operation of the train also played a part. From the aforementioned numbers the impression arises that low adhesion by the VIRM trains only posed a safety problem to a very limited extent. §2.2.1 establishes that this is not true for other types of rolling stock.

7.3.4 Cases of low adhesion during the period of measurement

From July 1, 2008 through February 1, 2009, 60 emergency brakes took place on the five measuring trains. Of these emergency brakes the driver applied 43 and 17 of them took place because the ATB (automatic train Influencing) intervened. In five of these emergency brake cases, slipping occurred during practically the complete braking process. In 4 of these 5 emergency brake cases the braking deceleration was adequate despite the slipping.

In one of these 5 emergency brake cases an average deceleration of just 0.51 m/s^2 was reached. (Deceleration during a emergency brake on a rough track is approximately 1.5 m/s^2). This deceleration is less than the required value mentioned in §7.3.2. But it is higher than the average weighed braking deceleration during the measuring period (see §7.3.1) 0.32 m/s^2. The braking distance for this emergency brake was 200 m. For this emergency brake it appeared that prior to activating the emergency brake a lot of slipping occurred. Therefore, it is likely that the emergency brake was applied due to the low adhesion situation.

It can be concluded that during the measuring period 1 braking instance led to an increased safety risk due to low adhesion. Considering the level of the actual brake deceleration the braking distance was probably not longer than what the driver intended.

7.3.5 Conclusions and recommendations

Based on the conducted research, it was ascertained that the safety risk due to low adhesion for the VIRM rolling stock is minor. This emerges from the fact that the number of red-signal passages due to low adhesion is minor and that during the measuring period an elevated safety risk occurred due to low adhesion in one braking instance only. Based on this, it seems that the braking process (combination of operations and braking system) on a slippery track practically meets the required level. But because it only occurred in one instance measured by 5 trains (not a representative sample) it cannot be evaluated how high this safety risk is. Therefore it also cannot be estimated whether the VIRM's braking system is indeed adequate.

In order to obtain insight into the safety risks due to low adhesion and to obtain insight into whether the VIRM (other rolling stock required if necessary) is adequate, it is advisable to conduct this research again but then with more VIRM tribo trains, during a longer period and if necessary with more measuring trains.

Within the scope of: ERTMS, program high frequent track (PHT), increasing the maximum speed to 160 km/h, reducing the distance between signals where possible, it is important to have good insight into braking distances and into the peaks in the braking distance for the various types of trains. By setting the system up to offer minimum, yet still safe braking distances, the track capacity can be optimally be utilized. This research has ascertained that obtaining information on braking distance and peaks in braking distance is relatively simple. It also shows that, in case of a peak in the braking distance, a low adhesion situation can be defined as the cause.

7.4 Cause of driving time loss due to low adhesion

Chapter 2 and 3 mention the causes for driving time loss: driver brakes more carefully, wheels that during acceleration cannot transmit the required force and/or reduced traction power applied by the driver. The research in this paragraph is aimed at acquiring this insight and to answer research question 3. The reason for knowing the cause for the driving time loss is that the cause influences the choice for which measures to take.

Researching the cause for the driving time extension is difficult because so many aspects play a part such as, for instance: timetable, difficulty to achieve the driving time on a certain section, busyness on the section, signal positioning in the track, failures in the infrastructure, failures in the train, type of train (train performance).

7.4.1 Research into the effect of low adhesion on the driving time

This paragraph offers insight into the driving time loss caused by low adhesion. This will be done by establishing the average driving times on a number of partial sections with and without low adhesion. Partial section means a ride from station A to the next station B where a stop is made. The driving time is the time it takes a train to get from station A to station B. The driving time loss is the extra time that a train takes for a partial section as a result of low adhesion. The average driving time for the various partial sections is subsequently compared to 1) The driving time in the period with the highest level of adhesion and 2) The driving time on the routes with the highest level of adhesion.

Below it is further explained which sections suffer from low adhesion and which do not. Also is further explained the definition for the period with the highest level of low adhesion occurs and the definition for the rides with the highest levels of low adhesion. Also it will explain how average driving times are established.

<u>Partial sections with low adhesion and without</u>
§7.5 will show that on the route Utrecht-Arnhem, the VIRM tribo trains detected a lot of low adhesion situations. Low adhesion was measured at all stations on this route, except for Utrecht Central. Between Den Helder and Zaandam the VIRM tribo trains detected barely any low adhesion. For the following slippery routes the average driving times were deteremined: Ede Wageningen-Veenendaal de Klomp, Utrecht Central-Driebergen Zeist and Ede Wageningen-Arnhem. In additon average driving times were determined for the following routes where no low adhesion occurred: Schagen-Heerhugowaard and Heerhugowaard-Alkmaar Noord.

<u>Periods with low adhesion</u>
§7.5 will show that in October 2008 and especially in November 2008 the VIRM tribo trains detected many low adhesion situations. The period with the highest level of low adhesion was between November 7 and 15, 2008.

<u>Low adhesion rides</u>
Whether a ride is considered a low adhesion ride is based on the gravity (see §7.1). For each ride on a partial section the level of gravity will be determined. If the level of gravity during a train ride is higher than a certain limit, the ride is considered as a low adhesion ride.

<u>Establishing average driving time</u>
The average driving time was calculated by determining the average of the average driving time per month. Therefore each month weighs in equal, despite the fact that the number of rides per month varies. Therefore it is not an average of all rides combined.

<u>Qualifications train ride to determine average driving time</u>
Low adhesion is not the only factor that influences a train's actual driving time. In order to be able to reliably compare the different train rides, a train ride must meet a number of demands before it can be included in the calculation of the driving time. The rides that are included in the calculation of the average driving time are the rides that have an equal velocity profile. If, for instance, a train has to wait along the way for a red signal, that is not caused by low adhesion, and therefore that ride will not be assessed. This way phenomena that have nothing to do with low adhesion are filtered out.

7.4.2 Equation of results for driving times

Table 7.4 shows driving times for various routes in the various mentioned situations. The first column lists the routes. The second column lists the average driving time for the given measuring period. The third column lists the average driving times during the slippery period between November 7, 2008 and Novemer 15, 2008. The last column lists the average driving times for the low adhesion rides on the slippery routes. On the routes without low adhesion, only a few slippery rides took place and therfore it is impossible to calculate a reliable average driving time for those rides. Therefore, these averages are not included in table 7.4.

		Average driving time (s)		
	Route	**Total measuring period 1/7/'08-1/2/'09**	**Slippery Period 7/11-15/11**	**Slippery rides**
Slippery	Ede-Wageningen to Veenendaal de Klomp	307,5	325,1	354,5
	Veenendaal-De Klomp to Ede Wageningen	315,4	342,9	342,3
	Utrecht central to Driebergen Zeist	489,5	493,8	491
	Driebergen-Zeist to Utrecht Centraal	478,3	506,9	506,1
	Ede Wageningen to Arnhem	617,2	644,1	649,7
	Arnhem to Ede Wageningen	645,8	670,9	690,7
Not slippery	Schagen to Heerhugowaard	485,2	489,9	
	Heerhugowaard to Schagen	488,4	487,5	
	Heerhugowaard to Alkmaar Noord	247,7	251,0	
	Alkmaar Noord to Heerhugowaard	254,0	256,1	

Table 7.4 Average driving time per route.

Observations
In table 7.4 the following stands out:

1. At slippery stations during the slippery period and slippery rides the average driving time is higher than the average driving time for the total measuring period. The difference in time is approximately 20 to 30 s.
2. At stations where no low adhesion occurs there is little to no loss of driving time for all of the three situations.
3. The average driving times from Utrecht Central to Driebergen Zeist are equal. Whereas a large part of this route is along a track with low adhesion. Further along in this paragraph a logical explanation will be given for this.

It must be noted that the average for the entire measuring period also includes the slippery months. The difference between a period with low adhesion and that without is therefore larger than table 7.4 shows.

Interpretation

Considering the fact that at slippery stations an extended driving time is in fact observed but not at stations that are not slippery, it is very probable that the loss of driving time is caused by low adhesion. Considering the extent of the lost driving time observed during the period with low adhesion and during low adhesion rides (see table 7.4), it is highly probable that low adhesion had a large impact on the driving on time (punctuality) percentage dip during the fall.

7.4.3 Loss of driving time per month

On basis of the measurements it is known where and when the VIRM tribo trains drove. The amount of time it takes to drive from station A to station B can be established by applying the measurement data. Based on the driving times for the various, separate rides a monthly average can be established. On the partial section Ede Wageningen to Veenendaal de Klomp the average driving time per month was investigated (see table 7.5). Also this table shows the number of rides that the driving time is based on. Tables like this one were made for other slippery routes too; they show a similar picture (see reference [44]).

Month	Average driving time (s)	Number of rides
July	312,5	24,0
August	307,3	20,0
September	313,4	29,0
October	315,5	93,0
November	336,5	70,0
December	316,0	28,0
January	306,8	20,0
7/11 -15/11	342,9	45,0
Average	315,4	

Table 7.5 Driving times from Veenendaal de Klomp to Ede-Wageningen.

Observation
The driving time for the route Veenendaal de Klomp to Ede Wageningen is much longer in November. In October and December the driving times are hardly any longer than in the months with the shortest driving times.

Interpretation
The course of the observed driving time per month (see table 7.5) during the measurment period matches the course of the monthly driving on time percentage (punctuality) over the year (see table 2.1). This observation also suggests that the punctuality dip in the fall is caused by low adhesion.

7.4.4 Causes for loss of driving time

§7.3.1 suggests that low adhesion has a large impact on driving time. In this paragraph it will be further investigated where along the route the driving time loss occurs. In order to obtain this insight the velocity-distance-diagrams (figures 7.3 and 7.4) and the time-distance-diagrams (figures 7.5 and 7.6) are drawn up. These figures relate to the route Ede Wageningen-Veenendaal de Klomp and back. Diagrams for the other routes can be found in appendix C. In the velocity-distance-diagram the progress of the velocity is depicted as a function of the travelled route. In the time-distance-diagram the time is shown since departure from the starting station.

Insight is obtained by comparing the curve shapes during a period or ride with low adhesion to a period without low adhesion. Also, insight is obtained into the how the velocity is divided over the distance travelled and where on the route the loss of driving time occurs. The situations that were compared are: 1. The average for the total period (pink), 2. The average during the period with the lowest adhesion between November 7 through 15, 2008. And 3. The average for the rides with low adhesion (red). A ride is considered slippery if the noted gravity (see §7.1) per ride is higher than 500. The time difference between the blue (slippery period in November) and the purple (average for the period) is displayed in green.

Observations velocity-distance-diagrams
Below a number of the general observations regarding the velocity-distance-diagrams are listed:

1. The maximum speed for rides with low adhesion (red line) is lower than the maximum speed calculated average for all rides (pink line); this can be found in figure 7.3 and 7.4 for example.
2. During a period of low adhesion (blue line) and rides subject to low adhesion (red line) the maximum speed is reached only after a longer distance has been travelled than the maximum speed calculated for all rides (pink line); this is shown in figure 7.3 and 7.4 for example.
3. On routes without low adhesion (Schagen-Heerhugowaard and Heerhugowaard-Alkmaar noord) there is almost no difference between the development of speed during periods with low adhesion (blue line) and the average for the total measuring period (pink line); this is shown in figures C9 and C11 in attachment C.

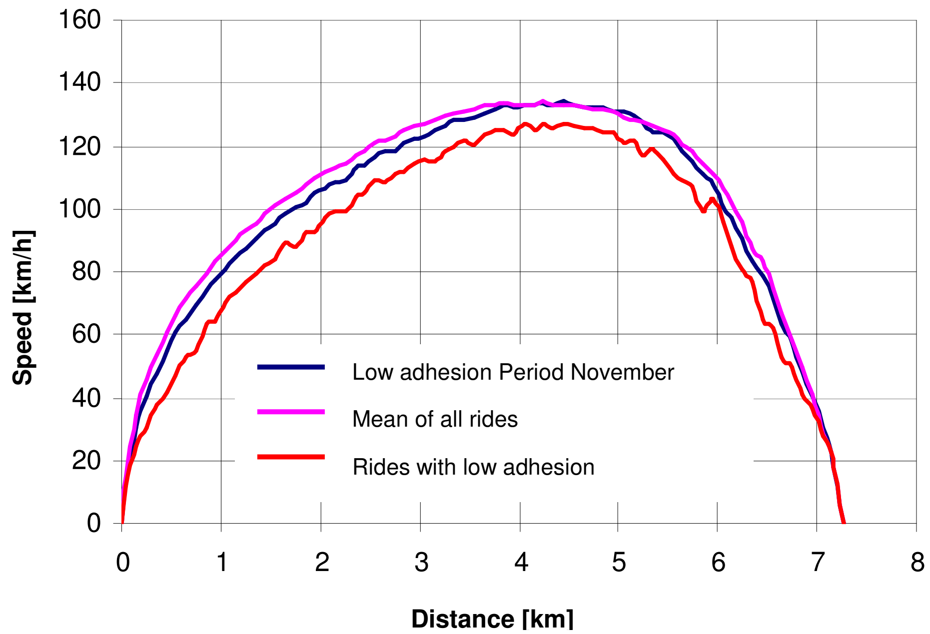


Figure 7.3 Velocity-distance-diagram from Ede-Wageningen to Veenendaal De Klomp.

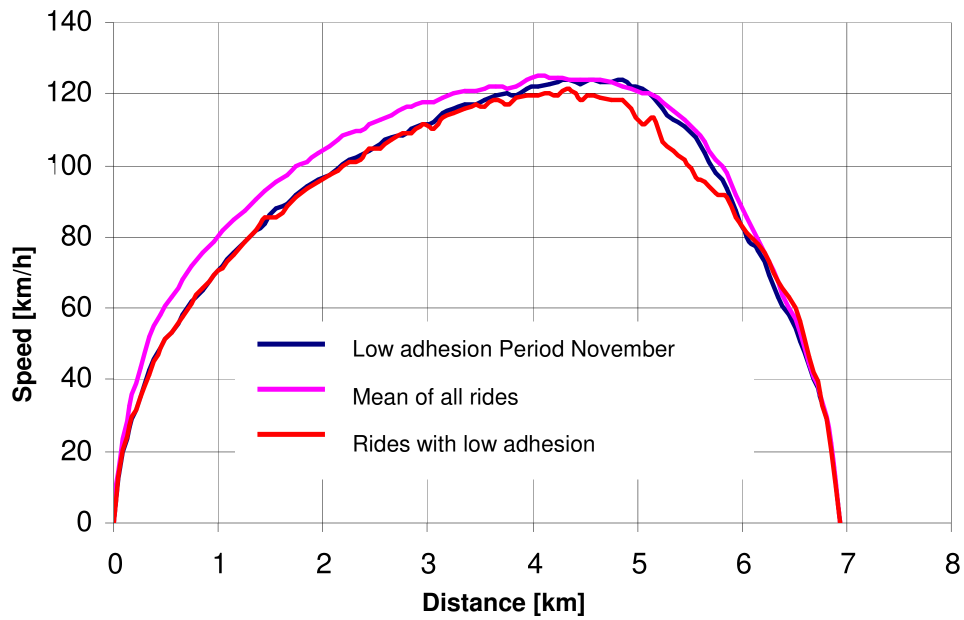


Figure 7.4 Velocity-distance-diagram Veenendaal-De Klomp to Ede-Wageningen.

Observations time-distance-diagrams

How the driving time loss builds up is illustrated in the following two examples:

1. On the route Ede-Wageningen to Veenendaal-De Klomp most of the driving time loss occurs during the first part (see figure 7.5). After two kilometers the driving time loss is 11 s. No further driving time loss occurs between the second and the fifth kilometre. At approximately 5 kilometers the braking process sets in. From 5 kilometres until full stop (kilometre 7) the driving time loss increases another 3 s tot 14 s.
2. The aforementioned also applies to the route Veenendaal-De Klomp to Ede-Wageningen (see figure 7.6). During acceleration in the first two kilometres, the driving time loss increases with 21 s. Between 2 and 5 kilometres the driving time loss only increases by 1 s. After kilometre 5 until full stop the driving time loss increases by 8s to a total of 30 s.

The following observations took place based on the time-distance-diagrams:

1. On the routes with low adhesion (Driebergen Zeist-Utrecht Central, Veenendaal de Klomp-Ede Wageningen en Ede-Wageningen-Arnhem) during the periods with low adhesion (blue line) and rides with low adhesion (red line) the larger part of the driving time loss occurs during the first kilometre of the train ride (see for example figure 7.5 and 7.6 and figures C in attachment C2, C6, C10, C12, C14 and C16). The relation between driving time loss due to braking and acceleration is in proportion of 1 to 3.
2. For rides with low adhesion (red line) on routes without low adhesion (Schagen-Heerhugowaard en Heerhugowaard-Alkmaar noord) the acceleration increase is also lower. It must be noted that these curves are only based on a few rides (less than 5 rides).
3. On routes without low adhesion (Schagen-Heerhugowaard and Heerhugowaard-Alkmaar noord) there is no difference between the average driving time during the measuring period (pink line) and the average time during the period with low adhesion (blue line). This is shown in figures C10 and C12 in attachment C.
4. In figure C4 in attachment C (Utrecht to Driebergen-Zeist) a difference does not occur during acceleration between the various categories from 0 to approximately 2 kilometres.

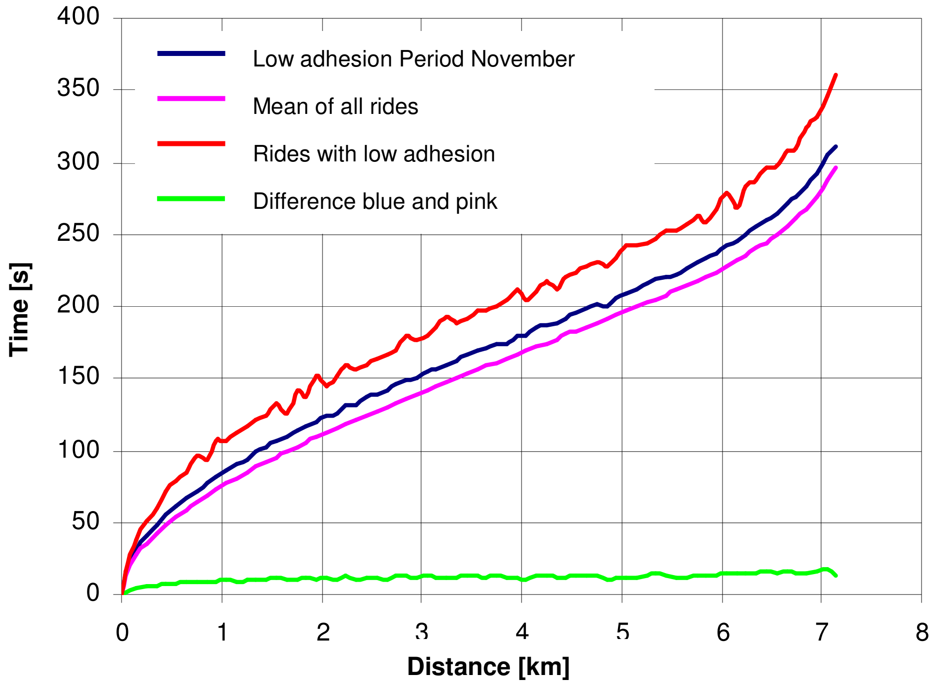


Figure 7.5 **Ede Wageningen to Veenendaal de Klomp.**

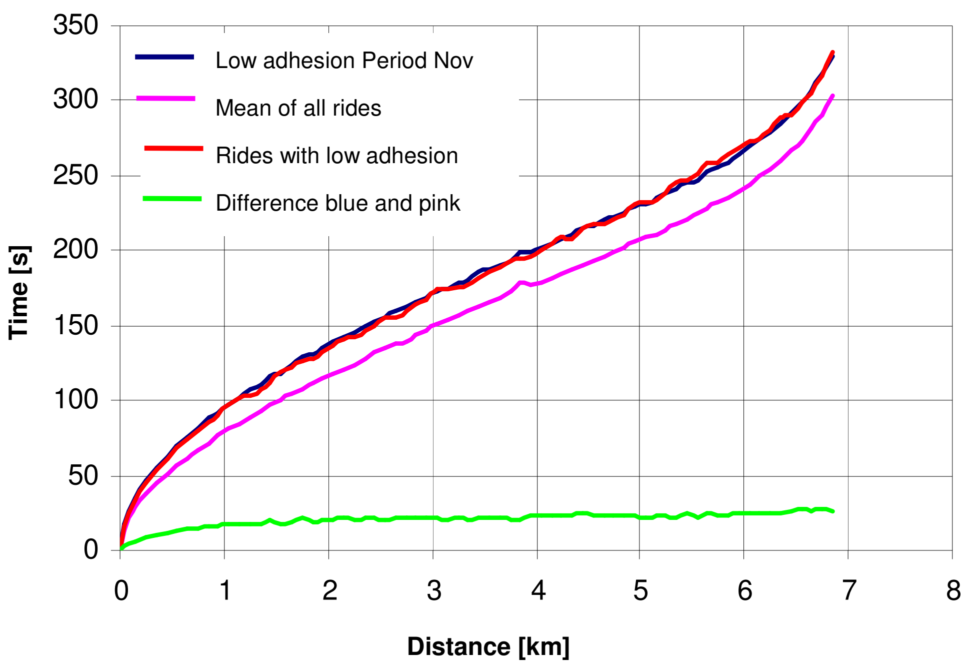


Figure 7.6 **Veenendaal-De Klomp to Ede-Wageningen.**

Interpretation
The observations made can be interpreted as follows:

1. The charts show that in case of low adhesion acceleration is less effective resulting in driving time loss. It must be noted that due to the fact that in case of low adhesion less acceleration takes place during the first kilometre the driving time loss will continue to increase until the maximum speed is reached. There are two possible explanations for the fact that acceleration is less effective:
   a. Due to slippery tracks the train cannot accelerate as well because the motor torque cannot be transmitted to the track.
   b. Drivers reduce motor torque if low adhesion occurs resulting also in reduced motor torque for the motors that are not slipping. Therefore the wheels that are not slipping transmit less force than required. A possible reason for the drivers to reduce motor torque is that they are used to doing so on other (older) rolling stock types to prevent damage to the rolling stock and/or to prevent reduced comfort.
2. The NS conducted tests in 2003 with sanders on two trains (see reference [31]). During these tests they tried to find out to what extent the sanders limited the loss of driving time. This research did not show a significant shorter driving time for the trains equipped with sanders compared to the reference trains. An explanation for this could be that the drivers on the trains equipped with sanders did not adjust their behaviour to the improvement (sanders). And therefore did not utilize the technique resulting in no significant improvement for the driving time.
3. The driving time loss found during braking can only occur because a driver (justly or injustly) adjusts his behaviour to the situation. In order to ensure that drivers do not change their behaviour if they expect low adhesion it is important that a driver can rely on a certain minimum braking distance.
4. §7.3.1 states that this paragraph will offer an explanation for the observation that the average driving times from Utrecht to Driebergen-Zeist show practically no loss of driving time in November despite the fact that a large part of the route is on track that are noted for their low adhesion. This observation can be explained based on the fact that driving time loss mainly occurs during acceleration at stations with low adhesion. In §7.5 it will be ascertained that Utrecht Central does not belong to stations where low adhesion often occur. Therefore it is obvious that on the mentioned route no loss of driving time occurs during the period with. This explanation is in accordance with figure C3 in attachment C.

7.4.5 Analysis driving time loss per ride

The previous paragraph focused on average driving time for a large number of rides during a certain period or during a certain minimum low adhesion situation. In order to get a better picture of the separate rides this paragraph will offer insight into the velocity-time-diagrams (see figure 7.7 and 7.8) for all separate rides.

Attachment D includes charts that show the progress of velocity for the separate rides during July and August, October and November per period set against the driving time for both directions on the route Ede-Wageningen to Veenendaal-De Klompt (see figures D1 through

D4). The chart indicates in colors, respectively green, yellow and red, whether the train had no, little or a lot of problems due to the low adhesion.

Observations

The following observations were made based on the mentioned figures:

- For low adhesion rides (red rides) the acceleration generally is much lower than the average acceleration, especially during the first kilometer.
- Low adhesion (red rides) on the route Veenendaal de Klomp Ede-Wageningen (7 kilometer) and vice versa can lead to a driving time loss of over one minute (figure 7.8 and D4).
- Figure 7.8 shows that in November five out of six rides inconvenienced by low adhesion experienced extended driving time.
- In October and November, the VIRM tribo trains suffered significantly from low adhesion. This can be ascertained from the fact that the diagrams for those months indicate that many red and yellow rides took place. A tendency between driving time and the color of the ride is perceived. The driving time for the yellow rides is on average longer than green ones and those of the red rides is on average longer than the yellow rides (see figures 7.8 and D4).
- There were also rides that took place during low adhesion situations (red rides) but for which the driving time still remained relatively short (see for example figures D1 and D4).

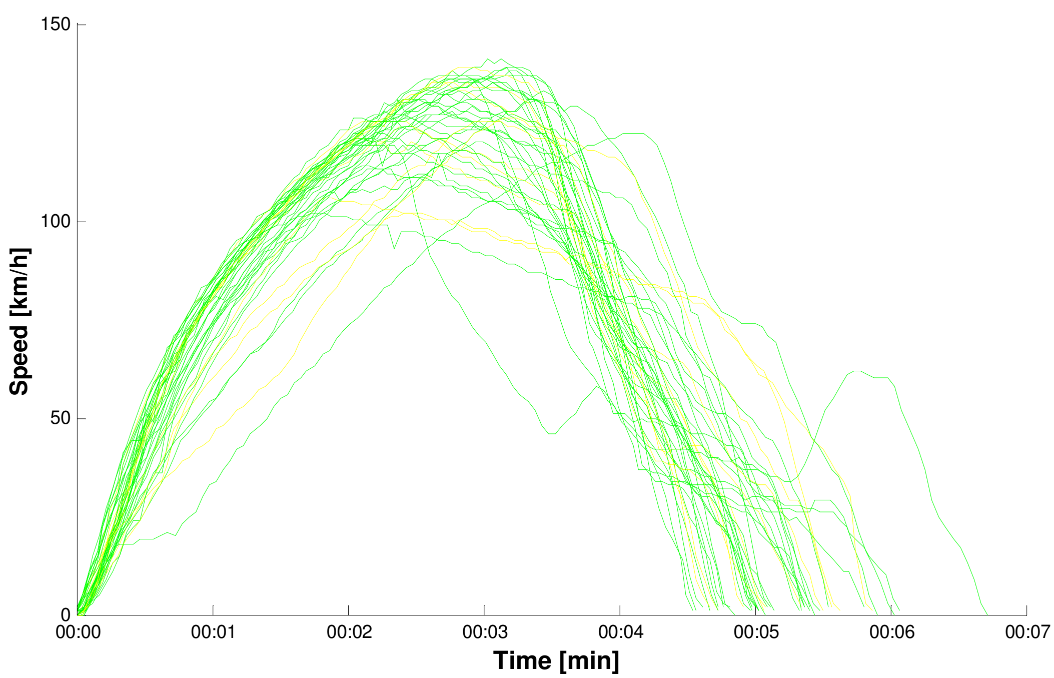


Figure 7.7 Speed-time diagram on route Veenendaal-De Klomp to Ede-Wageningen (August 2008).

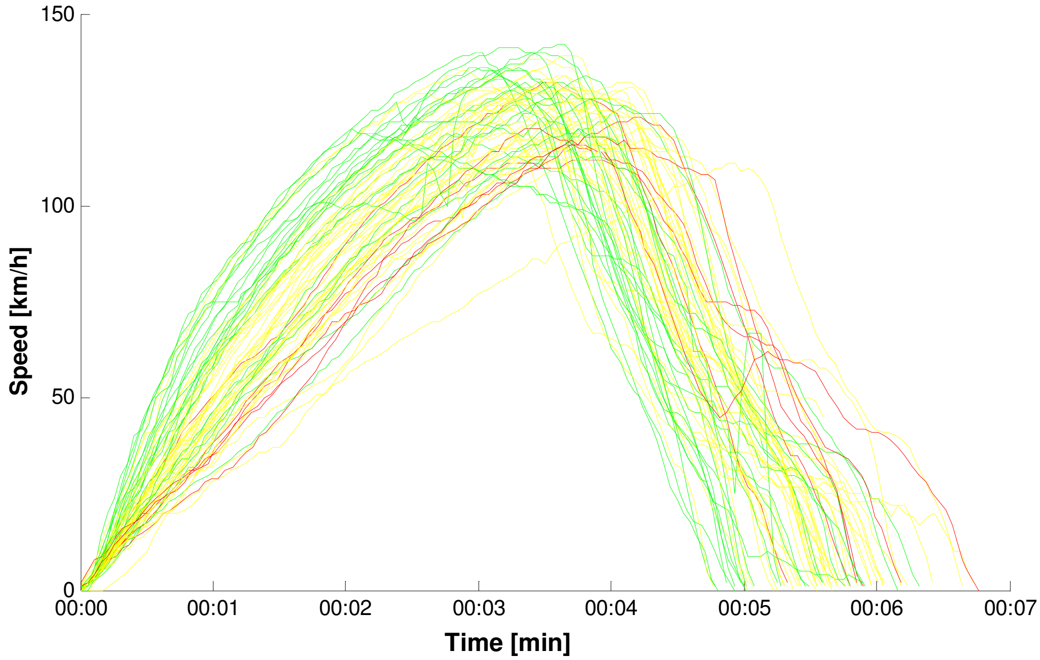


Figure 7.8 Speed-time diagram on route Veenendaal-De Klomp to Ede-Wageningen (November 2008).

7.4.6 Effect of driving behaviour during acceleration on driving time

The previous paragraphs show that loss of driving time due to low adhesion mainly occurs during acceleration. §7.3.4 states that this is caused by the fact that the train wheels cannot transmit the force required by the driver to the rail and that the driver can further reinforce this effect by his driving behaviour. This paragraph will ascertain that the driver's behaviour plays a part in loss of driving time during low adhesion situations. An estimate will also be made for the magnitude of the effect.

Traction level-distance diagrams

The velocity-distance and time-distance diagrams are mentioned in §7.1. Traction level-distance diagrams can be drawn up in a similar way (see figure 7.9 and 7.10). In that case the traction level applied by the driver (vertical axis) in percentages of the maximum motor torque is set off against the travelled distance. It has been ascertained that the driving time loss reaches its maximum during the first kilometer after leaving a station. It is also proven that the driving time loss is at it's most on the route Veenendaal de Klomp to Ede Wageningen. Therefore traction level-distance diagrams were only made for the first kilometer after the train leaves Veenedaal de Klomp in the direction of Ede-Wageningen.

In the traction level-distance diagrams the green line show that the observed gravity for the route Veenendaal de Klomp – Ede Wageningen is lower than 100. A red line shows an observed gravity higher than 750. For a blue line the observed gravity is between 100 and 750.

Observations

Figure 7.9 shows a traction level-distance diagram for July 2008; a period with little low adhesion. Figure 7.10 shows a traction level-distance diagram for the period November 9 through 16, 2009; the week with the highest level of low adhesion in 2008. Based on these figures the following can be observed:

- The average level of traction during the first kilometre in figure 7.9 is higher (approximately 80% than in figure 7.10 (approximately 55%). Also, the driver switches to a higher traction level earlier on during the route.
- The traction level during the first 100 m is higher in figure 7.9 than in figure 7.10.
- In figure 7.9 the driver changes the traction level less frequently than in figure 7.10. In figure 7.10 the driver changes during almost every ride; apparently this is what is taught.

In attachment E, figures E1 through E5 more traction level-distance diagrams are shown for the same route during different periods. These show a similar picture.

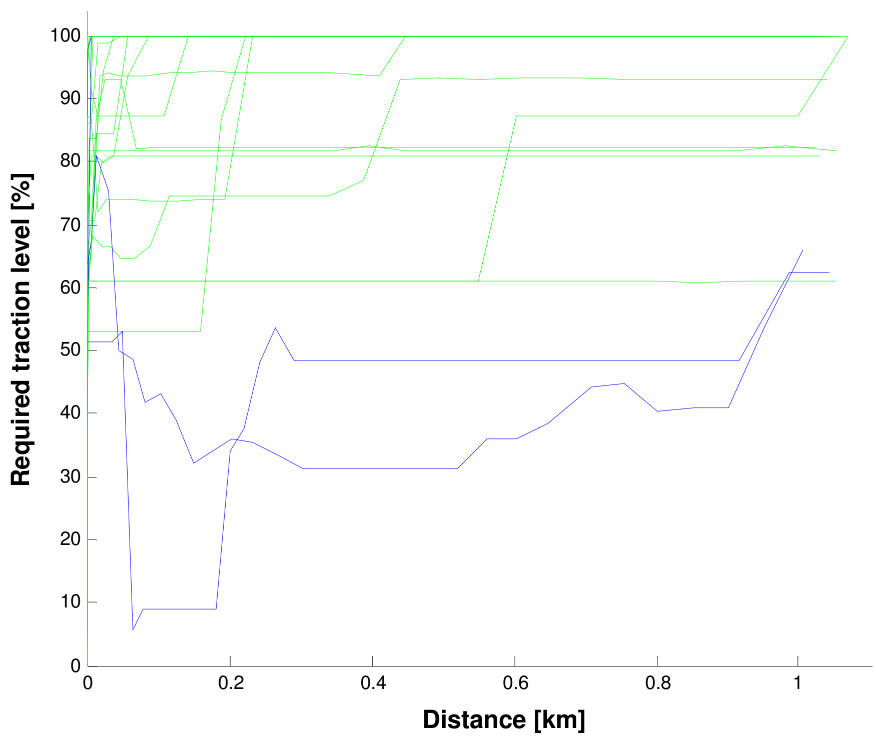


Figure 7.9 Traction level-distance-diagram from Veenendaal de Klomp to Ede Wageningen (July 2008).

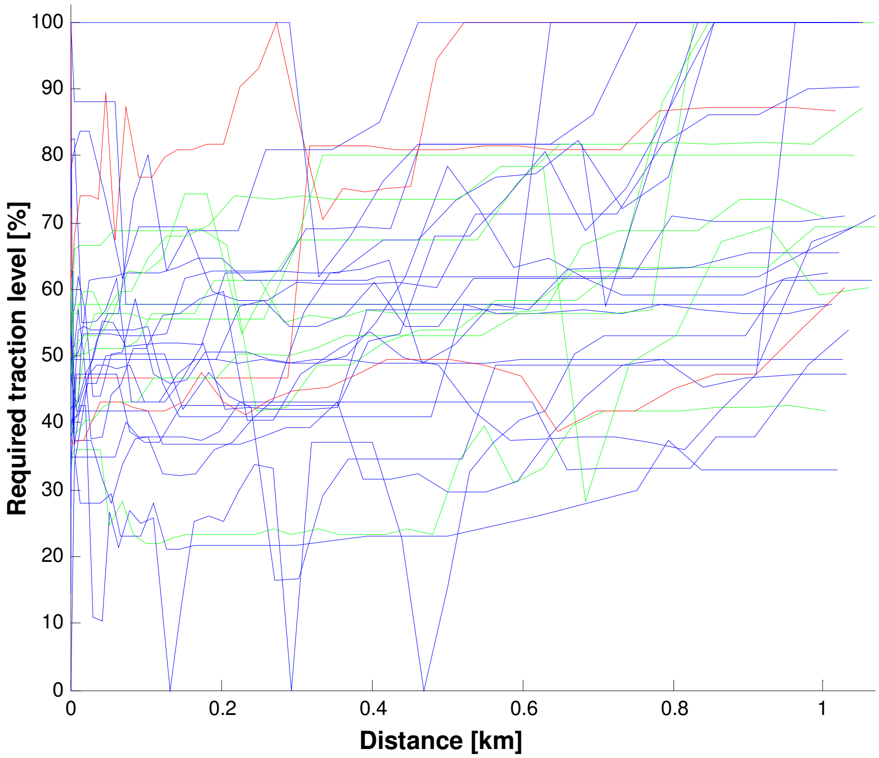


Figure 7.10 Traction level-distance diagrams from Veenendaal de Klomp to Ede Wageningen (November 9 through 16).

Figure 7.11 shows the traction level-distance diagram from Ede Wageningen to Veenendaal de Klomp during the week of November 9 through 16. In this figure the bottom (red) traction level-distance curve is notable. During the first 800 m it is so slippery that the wheels of the train start slipping as soon as the driver applies 20% traction torque. It is also notable that it is extremely slippery over a course of 800 m. This demonstrates that suchlike low adhesion over the mentioned distance happen.

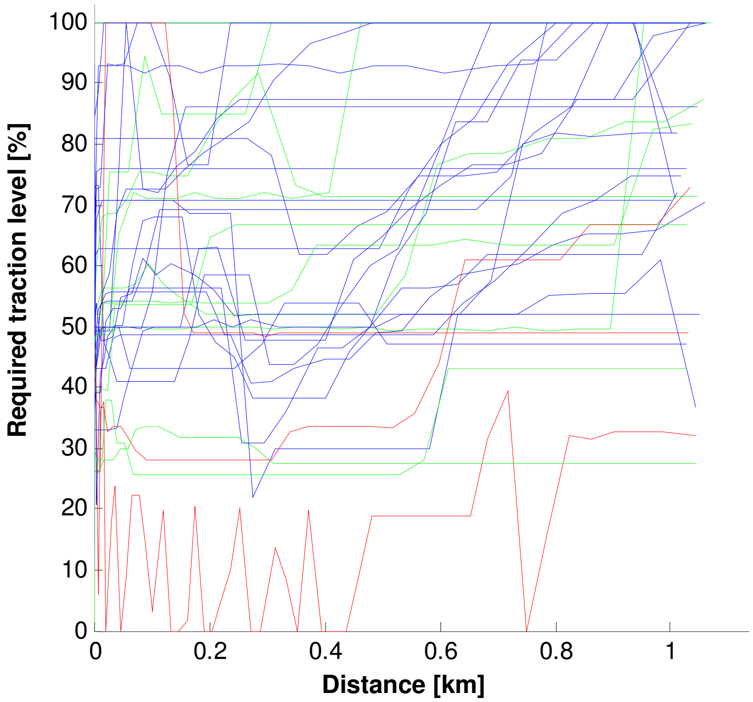


Figure 7.11 Traction level-distance diagrams from Ede Wageningen to Veenendaal de Klomp (November 9 through 16).

Reason

The reason why drivers choose a lower traction level if slipping occurs is probably because they want to prevent damage (wheel surface and shock absorbers) to the train and prevent reduced comfort. Also, drivers might feel that wheels that slip are a blemish to their professional honour. However, it can be discussed whether slipping wheels on modern rolling stock would lead to wheel damage.

7.4.7 Significance of the findings

<u>It is important to know that the effect of the driver on the driving on time (punctuality) and on the safety plays a role. If measures are taken without the driver adjusting his driving behaviour it is very well possible that the implemented measure will not lead to improved driving on time (punctuality) percentage.</u> It might lead to an increased level of safety, but because there are little or no safety problems due to low adhesion for VIRM trains the safety benefits are minimal.

7.4.8 Conclusions and recommendations

The research question that is answered in this paragraph is research question 3: Is the driving time loss in the fall caused by low adhesion and if so does it occur during acceleration or braking and what is the driver's influence on this. The following conclusions for this research question were drawn:

- It has been shown that the driving time is substantially extended due to low adhesion.
- It has been made plausible that low adhesion is a major cause for the driving on time dip (punctuality) during the fall.
- The driving time loss mainly occurs during the first kilometer of a route. The driving time loss during acceleration is in proportion of 1:3 to braking.
- The driving time loss during braking occurs because the driver starts the braking process sooner due to (possible) low adhesion.
- It was ascertained that drivers operate the traction lever differently during situations with low adhesion thus affecting the driving time loss.
- When implementing a measure to reduce the effects of low adhesion on driving on time (punctuality) and driving time it is necessary to consider the driver's driving behaviour.

The following recommendations are made to reduce driving time loss due to low adhesion during the braking process:

- Investigate whether the VIRM's braking system is adequate (see §7.2)

  If so:
  - Teach drivers new braking behaviour.

  If not:
  - Improve the braking system so that no safety risks occur any more on slippery tracks; for instance by applying sanders and/or magnetic track brakes.
  - Test (for example with VIRM tribo train) to see if the new situation has led to the required safety level.

The following recommendations are made to reduce the driving time loss due to low adhesion during acceleration:

- Test why drivers adjust their behaviour towards traction during low adhesion situations.
- Investigate if the VIRM is capable of determining the perfect traction torque for slippery tracks without damaging the rolling stock.
- If so: teach drivers new traction behaviour (this is a relatively inexpensive measure because it requires no major investments in technical solutions).

- Take technical measures to improve acceleration performance for example:
    - In future, equip trains with more driven axes[2].
    - Optimize the traction control in order to enable optimal use of the existing adhesion.
    - Install sanders to increase the adhesion between wheels and rails.
    - Apply Sandite.
    - Investigate to which extent the findings in this report also apply to other rolling stock.

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[2] *Equipping trains with more driven axles offers other advantages also such as reduced abrasion of the wheel surface, reduced abrasion of the wearing parts of the brakes, being able to return more energy to the overhead cable. A disadvantage however, is that traction systems require more maintenance.*

7.5 Where and when is it slippery? And to what extent?

In order to be able to develop effective and efficient measures it is important to know where and when it is slippery. This paragraph offers insight into this aspect and therefore answers research question 4.

7.5.1 Low adhesion per day

In order to obtain insight into how low adhesion is divided over the days during the measuring period (from June 30 through January 30, 2009). To this end all events (see §7.13) with a level of gravity higher than 500, which occur on one day, are summed up; this will be referred to as the summed up gravity per day. Figure 7.12 shows the summed up gravity per day for all trains combined during the period in which the measurements took place.

Observations

In figure 7.12 the following stands out:

1. In the period July 1 until September 1 low adhesion rarely occurred.
2. Even beyond the fall season serious cases of low adhesion can occur as is shown by the peak that occurred on January 2, 2009.
3. The summed up gravity per day is much higher in the fall than in the rest of the year.
4. In the fall the summed up gravity can vary strongly from day to day. It was for example not extremely slippery on the day after the slippery day November 10. Low adhesion, therefore, can also disappear emergencyly. Also there are days in the fall when no low adhesion occurs.

Remark

From October 7 until December 9, 2008 the VIRM tribo trains drove on the route Nijmegen-Den Helder as much as possible. On average approximately 3 trains drove along this route. Beyond that period, trains were deployed random on routes throughout the Netherlands. The deployment of the measurement trains affected the measurement results.

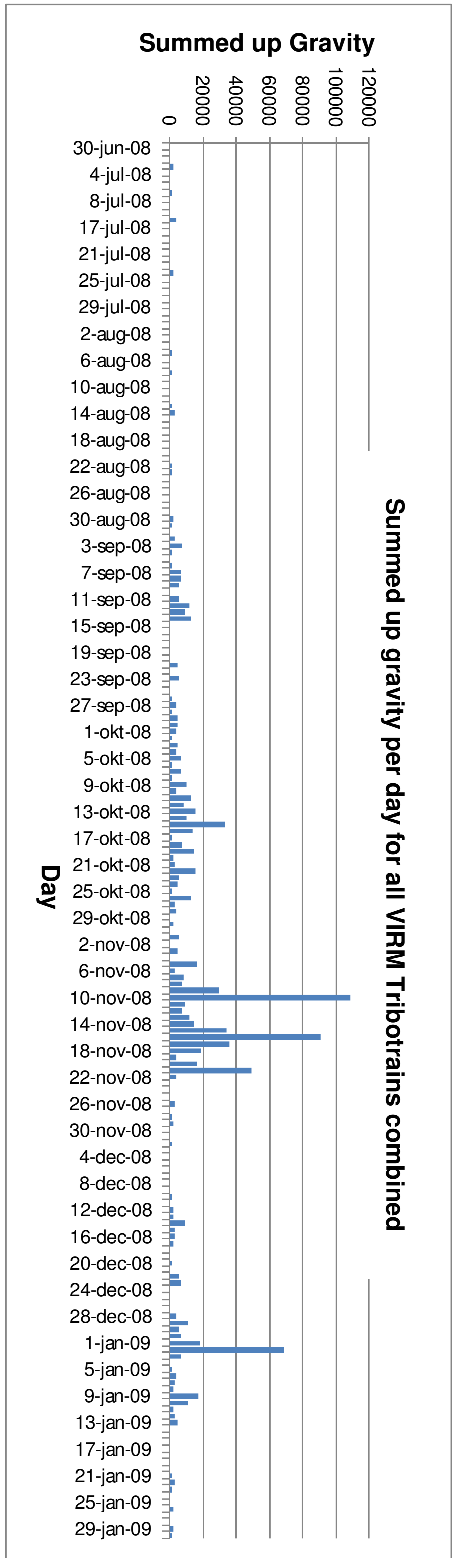

Figure 7.12 Summed up gravity per day; all VIRM tribo trains combined; whole measuring period.

7.5.2 Low adhesion per day per VIRM tribo train

Figure 7.13 shows the summed up gravity per day per day VIRM tribo train (multiple unit). In order to limit the amount of information only November 1 through 23 is displayed. This period was chosen because it was the period with the most level of low adhesion.

What is remarkable about this figure is that large differences in the summed up gravity per day per train can be found. It has been looked into to see if the number of driven kilometres on one day could explain the differences. It has been ascertained that if the distance driven is discounted large differences between the trains remain. The most logical explanation for this is that low adhesion occurs randomly; that from time to time and/or location to location large differences can occur. Whether a train comes across a section with low adhesion depends on this arbitrary occurrence.

7.5.3 How does low adhesion present on slippery days

All days with a very high summed up gravity (see figure 7.12) have been further investigated. The rough data was looked into to see how the high summed up gravity developed per day. It was ascertained that low adhesion on these days is mainly caused by a few events with a very high gravity level that occurred shortly after each other. Such a succession of events is called a cluster. The length of these clusters can amount to 20 to 40 kilometres. The summed up gravity per day as displayed in figure 7.12 is to a large extent dominated by a few clusters of events with a high level of gravity. It is not caused by a large number of smaller events. Attachment F describes a few of the most extreme clusters.

The clusters of events occurred in different places at different times during the day. In a cluster slipping can occur during braking as well as during traction. Per measuring train, the clustering of events usually occurs only once or a few times in two periods on a day. It also was ascertained that approximately half of them occurred between Nijmegen and Utrecht. On the route Utrecht-Den Helder no clusters of high gravity events occurred. It must be noted that most trains travelled the route Nijmegen-Den Helder during the fall. Therefore only on this route were sufficient measurements taken to be able to obtain insight into where low adhesion occurs regularly (hot spots).

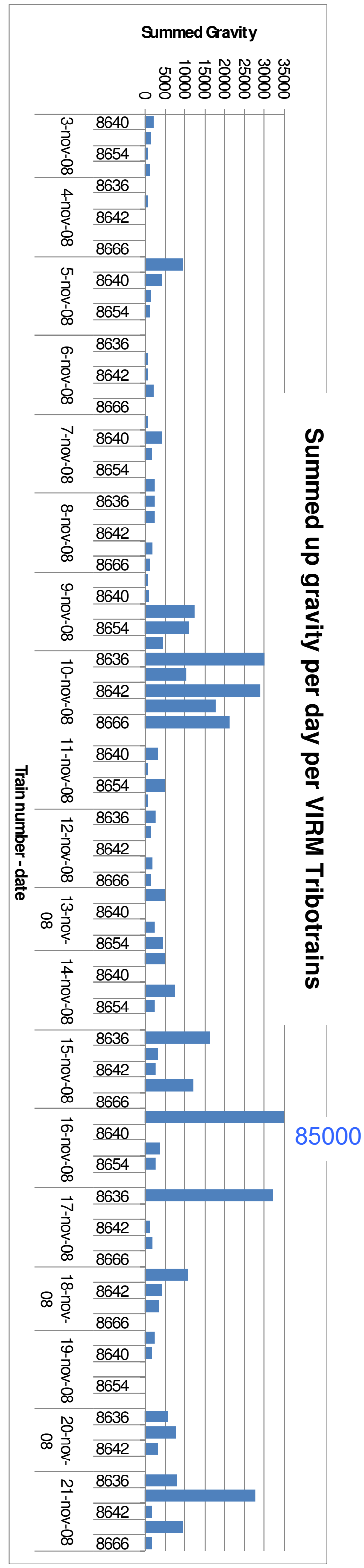

Figure 7.13 Summed up gravity per day per VIRM tribo trainset.

In a number of cases 2 VIRM tribo trains crossed each other when a cluster occurred or the train changed direction shortly after a cluster was passed. It was ascertained that on both of the track going and coming extreme cases of low adhesion occurred. This is not hard evidence as only a limited number of cases are concerned.

The observed clusters were presented to Meteo Consult (weather forecasting Company) to see if they can be explained by weather conditions. The results of the research conducted by Meteo Consult are not known yet.

Interpretation

A possible explanation for the clusters occurring and the random presentation of low adhesion in fall is: on days that a lot of leaves drop they are ran down onto the track forming a black layer. The layer becomes thicker every time a train passes. According to reference [34] and [24] the layer is more slippery than a dry track, but not so slippery that it causes problems. Not until the black layer becomes moist (rain, dew, fog, etc.) does extreme low adhesion occur. The black layer combined with moisture results in an emulsion that leads to extreme low adhesion. If this explanation is correct, it is obvious that the low adhesion will disappear after a few hours because the wheels drive the emulsion off of the rails. Apparently wheels in combination with a solvent (water) is a good way to drive the track clean.

7.5.4 Maps displaying events

In the method mentioned in §7.2.1 maps of The Netherlands were made indicating where slippery events occurred. In figure 7.14 such a map is shown for the period November 8 through 15, 2008; the most slippery period of autumn 2008. This map only shows events that occurred during acceleration.

Maps were also made for the subsequent periods showing the events that occurred: November 1 through 8, 2008 (acceleration and braking), November 10, 2008 (acceleration and braking), November 16, 2008 and January 2, 2009 (see appendix A figure A1 through A6). Note that the periods that various maps refer to are not equally long.

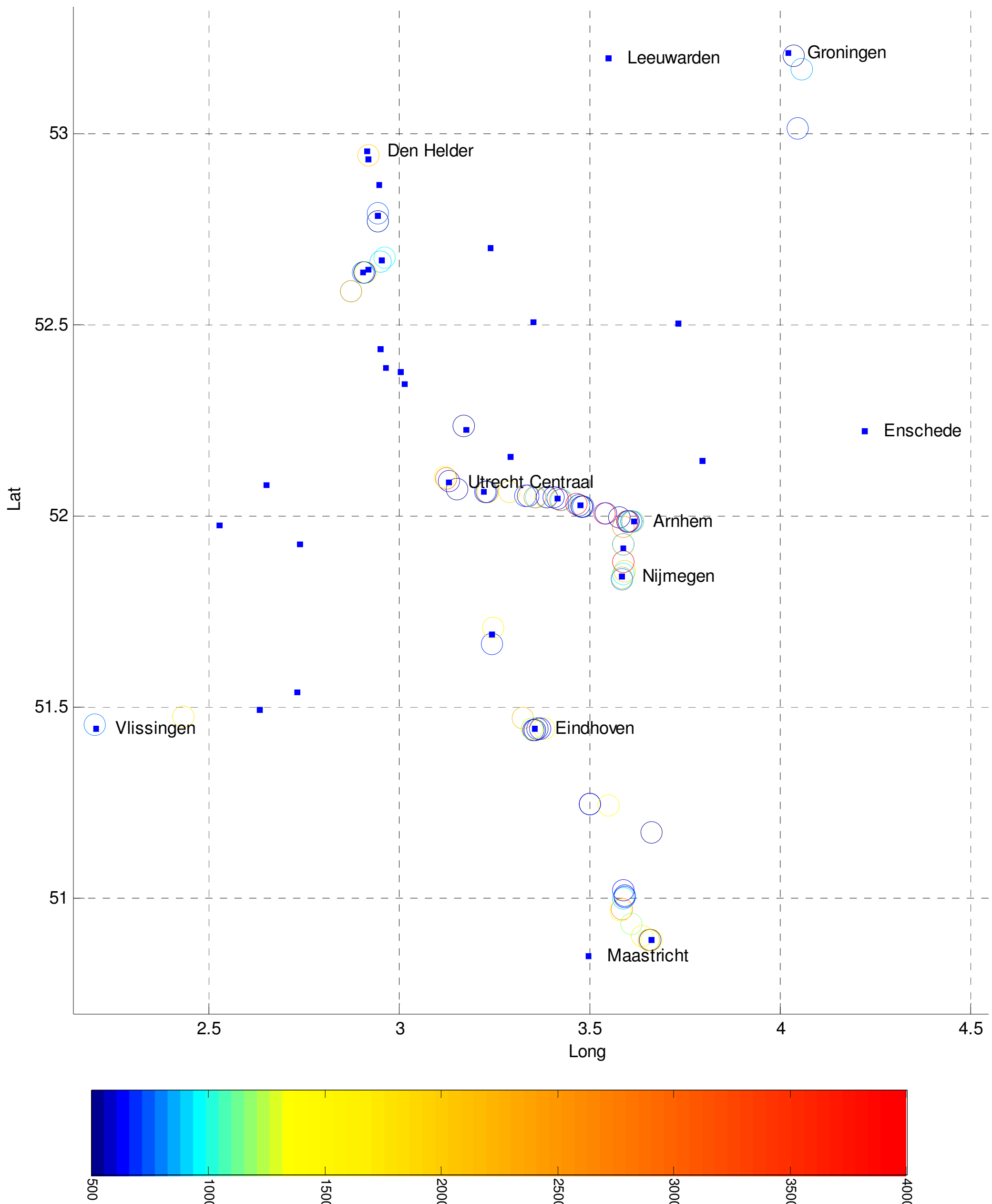

Figure 7.14 Slippery traction events in the period November 8 through 15, for all measuring trains combined.

Based on the mentioned maps the following observations can be made:

1. If figures 7.14 and figures A1 through A6 are compared it stands out that during the fall big differences in number and gravity occur per period per location for the occurring events.
2. If figures A1 and A3 are compared to figures A2 and A4 it stands out that events with a high gravity occur much more often during acceleration than during braking.
3. Figures 7.14 A1 and A3 show that during the research period large regional differences were observed. On the research route (Nijmegen-Den Helder) less low adhesion occurs

on the section Utrecht-Den Helder than on the section Nijmegen-Utrecht. The fact that low adhesion can occur very locally is also ascertained from figure A6 where extreme low adhesion occurred between Bodegraven and Leiden whereas in the rest of the country hardly any low adhesion presented. This instance shows that extreme low adhesion can also occur beyond the fall season. It must be noted that at most stations on the route Arnhem-Utrecht Sandite is applied.

4. Figure A5 shows that on November 16 on the Zeeland line events with high gravity occurred. At present it is not certain how often the measuring trains drove along the Zeeland line and therefore it cannot be assessed whether the low adhesion that occurred on November 16 was an incident or that the low adhesion occurs structurally.

7.5.5 Interpretation

Whether or not low adhesion presents is for the most part arbitrary. In order to be able to take effective and efficient measures it is important that measures can be applied with flexibility. The flexibility must ensure that no parts of the track are treated unnecessarily and that others unjustly are not treated at all.

7.5.6 Conclusions

This paragraph tries to answer research question 4: where and when is it slippery? In view of this research question the following conclusions can be drawn:

1. The extent of low adhesion can vary from location to location. On the route Den Helder-Nijmegen good insight has been obtained into where the slippery locations are.
2. Clusters strongly determine the extent of the summed up gravity per day.
3. Clusters occur very locally, at varying locations and times.
4. Large regional differences have been observed.

Based on these conclusions it can be established that measures can only be applied effectively and efficiently if they can be applied with flexibility. In practice this flexibility can only be obtained by situation dependent measures; see paragraph 2.3.

7.5.7 Recommendations

Based on the conducted research and corresponding conclusion the following recommendations are made:

1. Further research into where low adhesion presents on other routes.
2. Further research whether the locations where low adhesion occurs are interesting enough to add to the Sandite campaign.
3. It is recommended to research in more detail whether the cases of low adhesion detected on November 16 on the Zeeland line were random incidents or that the low adhesion is consistent.

7.6 Measurability/predictability of low adhesion

§2.3.1 shows that technical measures can be divided into two categories: location-dependent and situation-dependent measures. For location-dependent measures it is important to know where and when this type of measure needs to be taken. Based on a measurement/prediction an advice can be given on where and when low adhesion will occur; upon this can be determined where and when a measure has to carried out. The quality of the advice depends on how measurable/predictable low adhesion is. The measurability/predictability of low adhesion depends on how it occurs in daily practice; how fast low adhesion can vary in time and how much it can vary from location to location. This paragraph will offer insight into this aspect and will answer research question 5. §7.7 will offer insight into the quality of the existing low adhesion prediction model.

7.6.1 Variation of low adhesion in time

In §7.5 it was ascertained that low adhesion varies from day to day. In order to determine how measurable/predictable low adhesion is, it is important to know how fast low adhesion can vary from hour to hour (instead of from day to day). The time-distance diagrams mentioned in §7.2.2 are utilized to offer insight into how low adhesion progresses during the day. Figure 7.15 and figures B1 through B17 in attachment B are time-distance diagrams showing the Driebergen-Zeist, Veenendaal de Klomp and Ede-Wageningen routes.

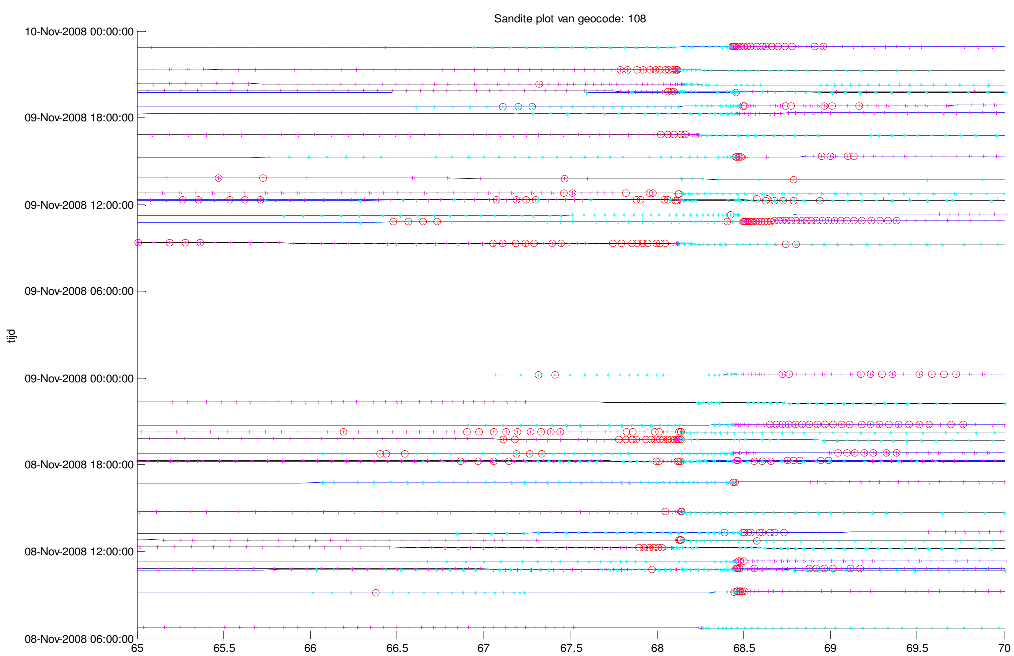

Figure 7.15 Time-distance diagram Veenendaal de Klomp November 8 and 9 2008.

Observations

Regarding the variation of low adhesion in time, the following stands out:

- Big differences in low adhesion occur per day. Compare November 6, 11, 12 and 13 (little low adhesion) with November 8, 9, 10 and 14 (a lot of low adhesion). The days mentioned are shown in figures B2 through B17. The same observations can be found in §7.4.
- On some days low adhesion hardly occurs and if it does, those events are generally short-lived, for instance on November 11 (figures B5 and B10), November 12 and 13 (figure B11). On the other hand, on slippery days, slipping occurs, to a greater or lesser extent, during almost every train passage, for instance on November 10 (figure B12).
- Usually it is observed that when low adhesion occurs the trains that follow within 2 hours of each other also suffer from low adhesion.
- <u>Occasionally it is observed that extreme low adhesion occurs while the previous train (within one hour prior at the most) does not experience any inconvenience whatsoever from the low adhesion. This is illustrated by figures B5 and B8.</u>

7.6.2 Variation of low adhesion from location to location

In General

In §7.5 it was ascertained that one station suffers much more from low adhesion than the other. However, there are also stations that are hardly, if at all, inconvenienced by low adhesion. In §7.5 it was also ascertained that there are large regional differences and that serious low adhesion also occurs beyond the fall season, although this is rare.

Specific

Based on the time-distance diagrams as displayed in figure 7.15 and in figures B2 through B17 in attachment B, insight can be obtained into how low adhesion varies for the following slippery stations Driebergen Zeist, Veenendaal de Klomp and Ede Wageningen. Regarding the varying location where low adhesion occurs the following stands out:

- The following differences/similarities can be observed for the stations mentioned:
  - On November 6, 7, 12 and 13 little low adhesion occurs both at Ede Wageningen as Veenendaal de Klomp (see figures B3, B6, B8 and B11). Driebergen Zeist is left out of the consideration because fewer stops took place there.
  - On November 8, 9 and 10 a lot of low adhesion occurred at Ede Wageningen and Veenendaal de Klomp (see figure B4, B5, B9, and B10). Driebergen-Zeist is left out of the consideration because fewer stops took place there.
  - On November 14 and 15 Veenendaal de Klomp was a lot more slippery than Ede Wageningen (see figures B7 and B12).
- Driebergen Zeist, Veenendaal de Klomp and Ede Wageningen are known for their low adhesion situations. The meteorological circumstances are similar because they are close together. What stands out is that in general if low adhesion occurs at one station, low adhesion also will occur at the following stations if the same VIRM tribo train passes there, examples for this are:

  - For all three the low adhesion was hardly noticeable if at all on November 6 (see figure B3, B8 and B14).
  - All three experienced low adhesion on: November 10 around 11.30 am (see figure B5, B10 and B16).
  - Veenendaal de Klomp en Ede Wageningen both experienced a lot of low adhesion (from Driebergen Zeist no information is available because the train did not stop there): November 8 at approximately 1.00 pm (figure B4, B9 and B15), November 14 at approximately 10.30 am (figure B7, B12 and B17) and November 15 at approximately 5.00 pm (figure B7, B12 and B17).
- However, it also happens that one station does experience low adhesion and one of the other two does not:
  - On November 7 at approximately 11.00 pm low adhesion occurred at Ede Wageningen, but not at Veenendaal de Klomp or Driebergen Zeist (figure B3, B8 and B14).
  - On November 8 at 8.00 pm low adhesion occurred at Veenendaal de Klomp but not at Ede Wageningen. For Driebergen Zeist no information is available because the train did not stop there (figure B4, B9 and B15).
  - On November 9 at approximately 11.00 am two trains, each a half hour apart, passed, both driving in the direction of Arnhem. At Driebergen Zeist and Veenendaal de Klomp the first of the two experienced inconvenience caused by low adhesion; at Driebergen Zeist the second train in particular experienced a lot of inconvenience caused by low adhesion. It must be noted that at Driebergen Zeist and Veenendaal de Klomp the traction torque was over 50% during the first passing and less than 50% during the second (see figure B4, B9 and B15).
- In general low adhesion occurs both for the outgoing and incoming track (figures B3, B4, B10, B15).
- It must be noted that the through trains (trains that do not stop at a certain station) hardly, if at all experienced inconvenience caused by the low adhesion.

7.6.3 Interpretation

100% reliable low adhesion advice

From the observations mentioned in §7.6.2 it can be ascertained that low adhesion can vary emergencyly in time and that it can vary from location to location. This variation in the level of adhesion combined with the fact that all parameters that affect adhesion are not known makes it impossible to predict it 100 % reliable. In order to be able to adequately measure these variations many parameters need to be measured which is practically unattainable. Based hereon the conclusion can be drawn that offering an advice on low adhesion that is 100% reliable is practically impossible.

If a 100% reliable low adhesion advice is not possible then it also is not possible to use this advise for taking location-dependant measures to ensure that the friction goes beyond a certain minimum level (guaranteed adhesion level). It is also impossible to warn drivers with a 100%

certainty if the adhesion goes beyond a minimum limit, which would make it impossible to brake safely.

Good advice on low adhesion; however not 100% reliable
From the observations mentioned in §7.4.2 it can be ascertained that low adhesion often lasts a long time (at least one day) and that at the following stations investigated on the slippery days, low adhesion occurred at all stations. §7.5.3 also shows that if extreme levels of low adhesion occur, it is often slippery over a length of tens of kilometres. In addition, it was ascertained that one region suffers more from low adhesion than the other.

These observations indicate that it is not possible to offer an advice on low adhesion that is 100% reliable, but that on a more general level there are options. This general advice can be used to determine whether or not Sandite should be applied on a certain day in a certain region. This advice could also be used to send the drivers an alertness warning for a certain region.

A regional low adhesion advice is necessary in order to be able to conduct a measurement every two hours (rough estimate). On lines with 8 trains per hour in both directions that would mean that 1 in 16 trains would need to be equipped with a measuring system.

LAWS
As it appears that low adhesion can vary strongly from location to location and from time to time, it is also clear why LAWS (§4.2) did not work in the Netherlands. Drivers indicated that a LAWS alert was received where it did not prove to be slippery or that it was slippery but that no LAWS alert had been sent out. 17 LAWS trains are not enough to adequately conduct measurements for all of the Netherland and then connect a warning system to it.

7.6.4 Conclusions

In this paragraph an attempt was made to answer research question 5: how fast can low adhesion occur in time and to which extent does it occur at varying locations? In other words: how measurable/predictable is low adhesion? With regards to this research question the following conclusions can be drawn:

- In practice it is impossible to give an advice on low adhesion that is 100% reliable based on measurements or predictions.
- Therefore it also is impossible to guarantee a certain level of adhesion using (location dependant) measures that were taken after a local report of low adhesion takes place.

Regarding the practical measures, the following conclusions can be drawn:

- Because low adhesion can vary strongly from location to location and also can vary emergencyly in time a high level of flexibility for the measures is required.
- Large regional differences were observed, therefore there is a need for a more regional prediction model.

7.7 Effectiveness of the prediction model for low adhesion

In this paragraph, the quality of the prediction model for low adhesion will be assessed by comparing it with the VIRM tribo train measurements on a certain day. The period that this analysis refers to is October 5 through December 7, 2008.

7.7.1 Required information

Here the choices needed to compare the predicted and the measured values are explained:

<u>The prediction</u>
Meteo Consult created a model that can predict low adhesion. The most important parameters on which the prediction is based are: precipitation, wind, condensation, night frost and amount of leaves dropped. A prediction is given for 10 days in advance. An example of a prediction (from November 13 through 22, 2007) is displayed in figure 7.16.

Prediction of low adhesion							
Day	Date	Precipitation	Wind	Condensation	Frost	Slip indication	Leaves fall
Tue	13-nov	Moderate	Moderate	Yes	No	6	Moderate
Wed	13-nov	No	Moderate	Yes	Yes	3	Moderate
Thu	13-nov	No	Small	Yes	Yes	2	Small/moderate
Fri	13-nov	No	Small	Yes	Yes	3	Small/moderate
Sat	13-nov	No	Moderate	No	Yes	2	Small/moderate
Sun	13-nov	Moderate	Moderate	No	Yes	6	Small/moderate
Mon	13-nov	No	Moderate	Yes	Yes	3	Small/moderate
Tue	13-nov	No	Moderate	Yes	Yes	2	Small/moderate
Wed	13-nov	No	Moderate	No	No	2	Small
Thu	13-nov	No	Moderate	Yes	No	2	Small

Key to the symbols	
Small	0 - 2
Moderate	3 - 5
Much	6 - 10

Figure 7.16 Prediction of low adhesion including keys to the symbols for the period November 13 through 22, 2007

A number between 0 and 10 indicates the predicted extent of adhesion for a certain day. In which 0 means no elevated chance for low adhesion and a 10 means a significant chance of low adhesion. Also, a colour code was assigned, gravity with a value of 0, 1 or 2 is assigned a green code, and gravity with a value of 3, 4 or 5 orange and gravity with a value of 6, 7, 8, 9 or 10 is assigned the colour code red.

Table 7.6 shows the prediction for 1 day in advance during the period October 6 through December 7. In the table the colour code is shown per day, and a gravity value between 0 and 10 is shown per day.

Week 41	6-okt	7-okt	8-okt	9-okt	10-okt	11-okt	12-okt
	2	2	2	2	2	2	1
Week 42	13-okt	14-okt	15-okt	16-okt	17-okt	18-okt	19-okt
	1	1	3	3	2	3	2
Week 43	20-okt	21-okt	22-okt	23-okt	24-okt	25-okt	26-okt
	2	2	2	2	3	2	6
Week 44	27-okt	28-okt	29-okt	30-okt	31-okt	1-nov	2-nov
	3	3	3	3	2	3	3
Week 45	3-nov	4-nov	5-nov	6-nov	7-nov	8-nov	9-nov
	3	2	2	1	3	4	6
Week 46	10-nov	11-nov	12-nov	13-nov	14-nov	15-nov	16-nov
	10	7	5	3	2	1	1
Week 47	17-nov	18-nov	19-nov	20-nov	21-nov	22-nov	23-nov
	2	1	1	2	4	3	3
Week 48	24-nov	25-nov	26-nov	27-nov	28-nov	29-nov	30-nov
	2	2	2	1	0	1	2
Week 49	1-dec	2-dec	3-dec	4-dec	5-dec	6-dec	7-dec
	1	2	1	2	1	1	2

Tabel 7.6 Predicted low adhesion fall of 2008.

Low adhesion measurement

In order to compare the predicted value with the measured value, the measured value needs to be translated into a value per day. The summed up gravity per day (see §7.5.1) is an appropriate value for this purpose. Here too, events with a value under 500 are not included.

As mentioned, there is a large difference in the amount of kilometres travelled per day. On a day that many kilometres are travelled, it is likely that in absolute sense more low adhesion will be measured and therefore the summed up gravity will be higher. Taking the travelled distance into account therefore seems reasonable. Because not all trains travel equal distances on each day the summed up gravity per day is weighed against the kilometre performance for that day. As the travelled distance per day for the measuring trains was not determined, but the measuring time (number of samples per day) was, the summed up gravity per day is weighed against the driving time. In that case it is assumed that the driving time is proportional to the performance per kilometre. If on a certain day the measuring trains' driving time is too low the weighed summed up gravity per day will be assigned a negative value of -0.1 (see figure 7.17).

During the period September 5 through December 7, 2008 an attempt was made to have the trains follow the route Den Helder-Nijmegen as much as possible. This resulted in approximately 3 tribo trains driving along the route Den Helder-Nijmegen during that period. On that route the section Nijmegen-Utrecht is slippery (see §7.5.4) and the other sections are not or not at all slippery. The section Nijmegen-Utrecht is centrally located in the Netherlands. It is obvious that the prediction model should apply to such a centrally located route.

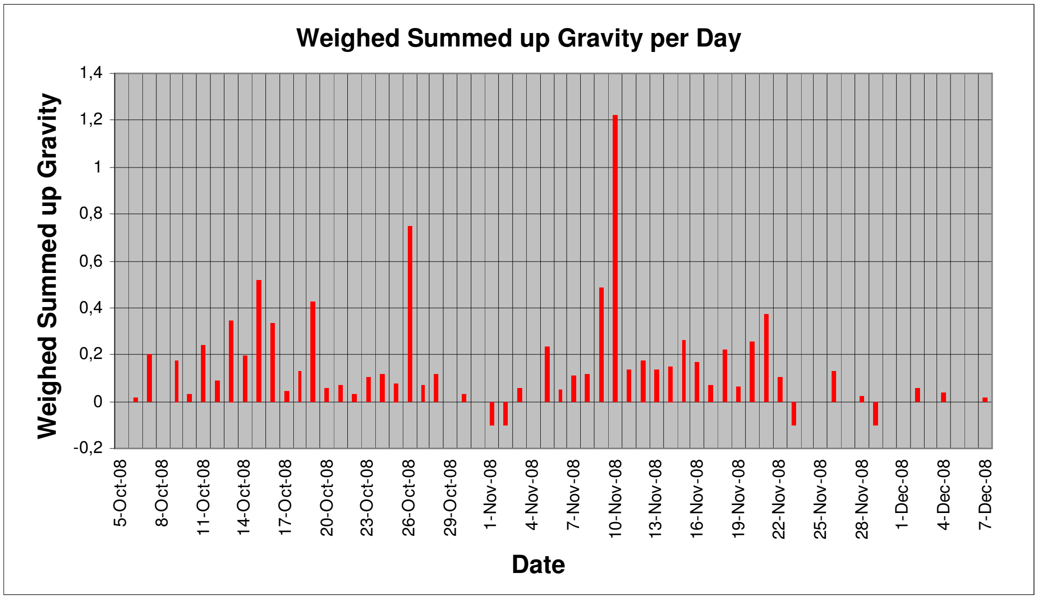

Figure 7.17 Weighed summed up gravity per day for the 3000-series.

The comparison

In order to judge the quality of the prediction model for low adhesion, the predicted low adhesion for one day in advance is compared to the measured weighed summed up gravity for the measurements on the route Den Helder-Nijmegen for that certain day. Figure 7.17 shows the weighed summed up gravity. Based on this chart, however, it is difficult to assign a colour code for the measured weighed summed up gravity. Which weighed summed up gravity value must be assigned an orange code and which value a red one. Therefore a different approach was taken. Two aspects were researched:

1. Were the peaks on days with a high weighed summed up gravity that were measured also predicted?
2. Were high weighed summed up gravity measurements found on days with a high, predicted gravity?

Results of comparison between predicted and measured gravity

The peaks with a high weighed summed up gravity that clearly stand out are the peaks with gravity over 0.4 (see figure 7.17). On October 15, 19 and 26 and on November 9 and 10, 2008 that value was exceeded. The peaks measured that occurred on October 15 and 19 2008 were not predicted (see table 7.6). On the other hand, the peaks measured on October 26 and on November 9 and 10, 2008 were predicted correctly. However, in contrast, a peak was predicted for November 11, 2008 but the measured weighed summed up gravity on that day was relatively low.

Another point that stands out is that the measured low adhesion (weighed summed up gravity) shows a changeable picture. There are days during the measuring period that it was not or not at all slippery, but there were also days that a lot of low adhesion occurred. The prediction shows a more constant picture.

Remarks:
Until now a prediction model for low adhesion has been designed without proper feedback on the actual low adhesion for the predicted day. Thanks to the development of the VIRM tribo trains it is now possible to offer correct feedback. By using the feedback, the prediction model can be improved. Improving the prediction model for low adhesion will further enhance the know-how about the problem, as relations will be able to be made between low adhesion, weather conditions and dropping leaves.

Conclusion
The following conclusions can be drawn:

1. The general idea that emerges is that the prediction moderately corresponds with the gravity value measured. There are days that unjustly too much low adhesion was predicted but there are also days that a lot of low adhesion was measured but that only a little low adhesion was predicted. However, the most extreme peak during the fall of 2008 on November 10 was predicted correctly. In order to be able to make a more precise statement on this subject more measurement information for slippery days will be required.
2. The prediction can be used to send out an alertness warning for drivers in particular and for NS-, ProRail-organisation and travellers in general. It is not accurate enough though to decide which measures need to be taken.

Recommendations
Being able to correctly predict low adhesion is important for: 1. Informing drivers, 2. Informing the railways (so they can prepare for low adhesion), 3. Informing travellers for possible inconvenience and 4. Determining when to start the Sandite campaign (and other measures). Considering the significance of the prediction model for low adhesion it is advised to further improve it.

1. §7.6 shows that low adhesion strongly varies from location to location and from time to time. This makes it very difficult to make predictions based on a national model. Possibly a regional or maybe even a local prediction model would work better. It is recommended to investigate if a local prediction model is feasible.
2. Until now a prediction model for low adhesion has been designed without proper feedback on the actual low adhesion for the predicted day. Thanks to the development of the VIRM tribo trains it is possible to offer correct feedback. By using the feedback the prediction model can be improved.

7.8 Assessing effectiveness of Sandite

Research question 6 is: what is the effectiveness of present measures and is it possible to guarantee a minimum braking distance using the existing measures. As mentioned in §2.3 until now only limited information is available on the effect of measures (as used in practice) in combating low adhesion. The reason that only limited information is available is that a measurement tool does not exist that can establish a relation between low adhesion and the effect of the measures. As a result it is not possible to draw up a cost/benefit analysis and therefore it is impossible to determine whether it would make any sense to invest in such a measure. Because only limited information is available on the effectiveness of measures against low adhesion it is difficult to optimize the existing measures. The VIRM tribo train is a tool that could possibly offer that insight.

In this paragraph research was conducted into whether the VIRM tribo trains can offer insight into the effectiveness of a location-dependent measure. In §7.9 it will be investigated whether the VIRM tribo trains can offer insight into situation-dependent measures. A location-dependent measure that is usually used in the Netherlands is Sandite. For this reason Sandite was chose to determine whether it is possible to use the VIRM tribo trains to obtain insight into the effectiveness of a location-dependent measure.

7.8.1 Sandite

Sandite is a gel containing sand and metal particles. The sand and the metal particles ensure that the adhesion on the track is increased. The gel ensures that the sand and the metal particles stay on the track longer, so that more trains benefit from the measure. The metal particles are used to make sure that the electrical resistance of the Sandite layer remains at a sufficiently low level, which is important for train detection (see §4.8). In the Netherlands, Sandite is applied on 6 running passenger trains on six fixed routes. One kilometre before and after a station, on one of the 6 routes, the treatment is applied.

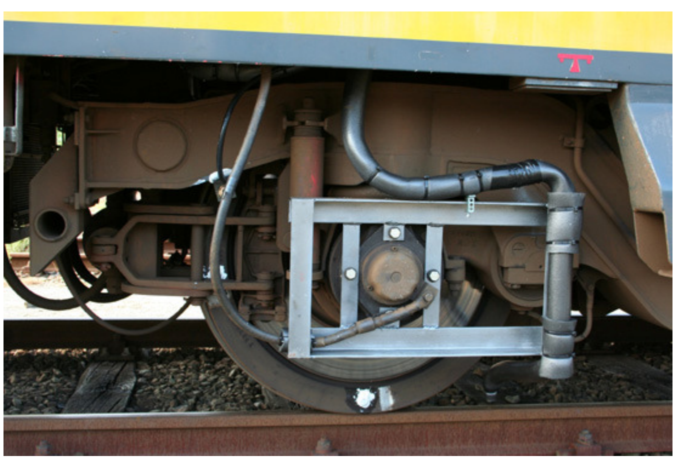

Figure 7.18 Installing Sandite system to the end of an axle.

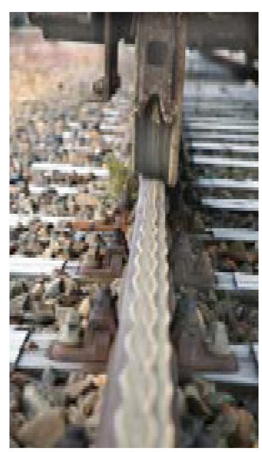

Figure 7.19 Sandite on the track.

7.8.2 Research approach to assess effectiveness of Sandite

In order to show the effectiveness of Sandite the time-distance diagrams are used as mentioned in §7.2. These time-distance diagrams show where and when Sandite was applied and also where and when slipping occurred. This allows a relation to be made between the application of Sandite and adhesion (whether or not slipping occurred).

In order to be able to answer the research question the information from the VIRM tribo trains is linked to the information from the Sandite trains (supplied by ProRail). With the information on the Sandite trains it is possible to find out where and when Sandite is applied and also in which direction the Sandite train was driving.

7.8.3 Preconditions for test set up

This research is intended to show that where Sandite was applied no/less slipping occurs than in locations where it was not applied. In order to obtain reliable insight into this aspect the test setup needs to meet certain demands:

1. It is necessary to have two track available that are similar as far as adhesion is concerned. On one track (the test track) Sandite will need to be applied. The other track (reference track) is intended to determine whether or not it is slippery.
2. It is important to be able to conduct sufficient measurements per day in order to be able to assess the progress of the adhesion.
3. Test and reference track must be known for their low adhesion.
4. The VIRM tribo trains must stop at both the test station as well as at the reference station.

In order to be able to conduct sufficient measurements the VIRM tribo trains were deployed on the route Den Helder – Nijmegen (3000 series). The application of the Sandite was not altered for this test. The test must be conducted based on method as it is applied in the existing campaign. On this route only the station Driebergen Zeist qualifies as test station. The following can be said for the other stations on the route:

- It is not slippery there (stations between Den Helder and Utrecht).
- No Sandite is applied on the track where the VIRM tribo trains drive (Nijmegen, Arnhem, Ede Wageningen, Veenendaal de Klomp and Utrecht).
- The VIRM tribo train does not stop at the station in question (for instance Wolfheeze).

Veenendaal de Klomp and Ede Wageningen can serve as reference station for Driebergen Zeist. Both stations are in each other’s vicinity and are known to be slippery. The problem with the test station Driebergen-Zeist is that the trains from the 3000 series do not stop there until after 8.30 pm. Luckily it turns out that there are many VIRM tribo trains in the 3100 (Nijmegen-Schiphol) that do stop at Driebergen Zeist.

Assessing the effectiveness of Sandite can only be done on slippery days when Sandite has been applied on the test route. Whether a day is slippery is determined based on the extent of low adhesion at reference stations Ede Wageningen and Veenendaal de Klomp. It must be noted that at station Ede Wageningen Sandite is applied, but not to the track where the measuring trains drive.

7.8.4 Results

How Sandite functions will be investigated in this paragraph. An answer will be given to the question: does Sandite prevent slipping?

On the following days a lot of low adhesion was detected at the reference stations: November 7, 8, 9, 10, 14 and 15, 2008. Attachment B shows diagrams regarding these slippery days for Ede Wageningen in figures B3 through B7, for Veenendaal de Klomp in figures B8 through B12 and for Driebergen Zeist in figures B13 through B17. When a specific case is referred to it is framed in the figure. The research is based on these days because these were slippery days during which relatively many VIRM tribo trains passed here.

Observations

The research into the effectiveness of Sandite only offered limited insight due to the fact that at the stations mentioned it was only really slippery on a few days and because not enough measurements per day were conducted.

What also was ascertained was that mainly in the two hours after Sandite had been applied not enough measuring trains stopped at Driebergen-Zeist. This period was the most interesting to assess the effectiveness of Sandite. In order to obtain a good insight into the effectiveness of Sandite more measuring trains will need to pass the test and reference location directly after Sandite has been applied.

For the above-mentioned reasons only limited judgement can be made on the effectiveness of Sandite. The observations are listed below:

- In general Sandite is applied once a day, this is done in the morning between 5.00 and 9.00 am. Sometimes Sandite is applied twice (also between 4.00 and 8.00 pm).
- Many trains that stopped at Driebergen Zeist slipped. From November 6 through 15, 16 trains stopped at Driebergen Zeist within 4 hours after Sandite was applied. 11 of the 16 measuring trains slipped. Examples of the slipping incidents can be found in figure B15 frame B15.1 and figure B16, frame B16.1.
- Every measuring train that stopped at Driebergen Zeist on November 8, 9, 10, 11 and 14 after 8.30 pm slipped (figures B15, B16 and B17).
- Many slipping incidents occurred at Driebergen Zeist on November 11 (figure B16) while at Ede Wageningen and Veenendaal de Klomp only a few cases of slip (low adhesion) occurred (see figure B5 and B10).
- It has happened that immediately after applying Sandite slipping occurred. An example of this can be found in figure B13, frame B13.1.

Interpretation

The following interpretations are assigned to the observations

- It can be said that Sandite does not function such that after it has been applied no slipping (low adhesion) occurs for the rest of the day.
- Because only a few measurements were conducted within two hours after Sandite was applied it cannot be assessed what the effectiveness of Sandite was during that period.
- The incident where slipping occurred immediately after Sandite was applied could also have been caused by an incorrect measurement:
    - The train was riding on a different track than the one where Sandite was applied.
    - The time synchronization between the VIRM tribo train information and the Sandite data is incorrect. In reality the Sandite train possibly passed just after the VIRM tribo train passed.
- Considering the fact that on November 11, 2008 much more slipping occurred at Driebergen Zeist than at the reference stations, despite the fact that at Driebergen Zeist Sandite is applied, indicates that the low adhesion between the test and reference stations is not (always) reliable. This shows that prudence is called for when drawing conclusions from this information.

7.8.5 Sandite Efficiency

Based on the time-distance diagrams (figures B1 through B17 in attachment B) it can be observed that on a large number of days during the fall it is not slippery. During the fall of 2008, Sandite was applied from October 20 through December 5; 46 days. On a large number of days therefore Sandite was applied unnecessarily.

The following estimate is made on the number of days that it was necessary/desired to apply Sandite. Of the 46 days it was very slippery on 6 of them, on 5 days only a few slipping incidents occurred and on 13 days it was not slippery at all. The remaining 22 days none or few measuring trains drove on the route Utrecht-Nijmegen so therefore it is not possible to make a correct estimation regarding the extent of the adhesion on those days. On these 22 days the measuring trains rode on different routes. From §7.5 it is clear that on 11 days of the 22 days hardly any low adhesion was measured. Based thereon it is assumed that on 24 of the 46 days it was not necessary to apply Sandite.

By using a good prediction model for low adhesion and/or by conducting many measurements the efficiency of Sandite can be increased. In that case, Sandite would only be applied if it really were necessary.

7.8.6 Improving the measurement method

For this research was not a special test setup developed. Therefore it appeared impossible to assess the effectiveness of Sandite. However, this research does offer a number of clues to develop a test setup that is expected to be able to determine the effectiveness of Sandite. For this the following will be necessary:

1. More measuring trains, especially after Sandite is applied. Considering the fact the VIRM tribo trains are relatively inexpensive this option could be realized.
2. Better choice of reference and test station. One possibility could be to use the incoming track as reference and outgoing track as test track.
3. More reference and test stations, so that more measurement information is available allowing a statistically more reliable assessment.
4. More influence on when Sandite is applied. By applying Sandite before the test from fixed installations (on the infrastructure) it can be determined when Sandite needs to be applied.

7.8.7 Conclusions effectiveness of Sandite

This paragraph is intended to answer the research question 6 whether it is possible to assess the effectiveness of a location-dependent measure (Sandite). Regarding this research question the following conclusions were drawn:

- Only limited insight into the effectiveness of Sandite was obtained:
    - It was indicated that the effectiveness of Sandite is limited.
    - Sandite does not function such that after applying no low adhesion (slipperiness) occurs the rest of the day.
    - A less effective aspect of the Sandite campaign is the fact that on 46 days Sandite was applied where it only needed to have been applied on 24 days.
- Only limited insight into the effectiveness of Sandite was obtained because there was not enough measurement information due to:
    - The measuring train density was not high enough.
    - Not enough slippery days (6) occurred at the test and reference stations.
    - It turned out to be impossible to find a suitable test station on the route Den Helder-Nijmegen.
- If the improvements mentioned for the test method are implemented, it is expected that a reliable insight will be able to be obtained regarding the effectiveness of Sandite (location-dependent measures).

7.8.8 Recommendations regarding effectiveness of Sandite

The most important recommendations deriving from this research are:

1. The research conducted indicates that Sandite is only limitedly effective. As € 20 million has been spent on the Sandite campaign during the past ten years and as a new investment in the Sandite campaign is to be expected shortly it is paramount to obtain insight into the effectiveness of Sandite (cost/benefit). A follow-up study might be able to offer more insight into the effectiveness of Sandite. This paragraph shows how that research could be conducted.
2. The principle of the VIRM tribo train could be added to the Sandite trains. In locations where low adhesion is detected Sandite could be applied. That would be an added

functionality to the existing functionalities. Also, if low adhesion is not detected Sandite would need to be applied at certain hot spots as a precautionary measure due to the fact that low adhesion can vary emergencyly in time.

7.9 Assessing the effectiveness of magnetic track brakes

In the previous paragraph a method was developed and implemented to obtain insight into the effectiveness of a location-dependent measure. In order to do so it is necessary to monitor a certain location. This method cannot be used for a situation-dependent measure because it is unknown where the measure would be implemented. That is why another measuring method was developed.

The basic principle for this measuring method is that the friction coefficient is measured before and after a measure has been implemented. In this paragraph research will be conducted into how the VIRM tribo train can offer insight into the effectiveness of a situation-dependent measure. A situation-dependent measure that is highly valued in the Netherlands is the magnetic track brakes. For this reason, the magnetic track brake have been chosen to determine whether more insight can be obtained into the effectiveness of a situation-dependent measure by utilizing the VIRM tribo trains.

If it is possible to determine the benefits of the magnetic track brakes (situation-dependent measures), it is also possible to draw up a cost/benefit analysis. That way it can be decided whether it makes sense to invest in magnetic track brakes.

7.9.1 Magnetic track brakes

The magnetic track brake works because a magnetic block pulls and fastens itself on the track. The friction between the block and the track causes the braking force. Because the magnetic block pulls itself against the rail the magnetic track brake supplies braking force and at the same time the rail is wiped clean. The leaves and other substances that cause low adhesion are removed from the rails by the magnetic track brake in a mechanical and thermal way. When the train is in motion, the magnetic track brakes can only be activated in case of a emergency brake. The emergency brake can be activated by the driver, by a passenger (emergency lever in the passenger cabin) or by the ATB (Automatic Train Influencing) system (system that takes over if a driver don't react on signals from the track) The driver cannot interrupt an emergency brake.

Figure 7.20 Magnetic track brake in action.

Figure 7.21 Magnetic track brake.

7.9.2 Research approach to assess effectiveness of magnetic track brakes

A VIRM train has six magnetic track brakes. Figure 5.4 shows where on the VIRM train the magnetic track brakes and traction installations (M_1, M_2 en M_7) are located. As a six coach

VIRM train has 3 traction installations/ED-brakes, adhesion can be measured in three locations in the train.

The bogies equipped with a traction installation/ED brake pass the spot where the magnetic track brakes were first activated in succession. In order to determine whether the magnetic track brake has a roughing effect, the friction coefficient measured by the traction installations/ED brakes need to be compared to each other on the spot where the magnetic track brakes were in contact with the track.

Figure 5.4 shows that irrespective of the driving direction one magnetic track brake is always positioned in front of one traction installation/ED brake. This means that when the magnetic track brake is used the first traction installation/ED brake (M_1 of M_2) conducts measurements where one magnetic track brake already has had an effect on the track. The roughing effect of the first magnetic track brake therefore cannot be determined (unless it is deactivated). Motor bogies number two and three ride over the area where respectively three and five have already been in contact with the track. If the magnetic track brake had a roughing effect, the friction coefficients measured by the second and third traction installation/ED brakes would be higher than the measured coefficient for the first traction installation/ED brake.

By using the traction installation/ED brake positions and the friction coefficients a chart could be made where the friction coefficients are set off against the position. This chart would enable the changes for a friction coefficient at a certain location to be analysed.

The measuring frequency is 1/3 Hz. This means that every three seconds a measurement is conducted. Therefore, the chance that the traction installation/ED brakes detect friction at exactly the same location is small.

7.9.3 Results/Observations conducted research into effectiveness magnetic track brakes

Number of emergency brakes

From July 1 through February 1, 2009, 60 emergency brakes occurred on the five measuring trains, either applied by the driver or by an ATB intervention. 60 emergency brakes boil down to approximately one emergency brake per 20 days per train. During five of these emergency brakes, almost for the duration of the total braking process, slipping occurred. To enable a good analysis of the effect of the magnetic track brake a series of emergency brakes over a length of more than 200 meters is required. For shorter braking distances the last traction installation/ED brake will not reach the location where all previous magnetic track brakes were because the braking distance is shorter than the distance between two consecutive traction installations/ED brakes. Therefore it would not be possible to compare the friction coefficients measured by the three traction installations/ED brakes. Only one emergency brake of at least 200 meters occurred on a slippery rail. Emergency brakes did occur, however, on slippery track with a length of approximately 80 meters.

Number of ATB brakes

From July 1, 2008 until February 1, 2009 17 ATB interventions occurred in the measuring trains. What stands out is that in 10 out of 17 interventions slipping occurred with all three traction installations/ED brakes at a certain moment but not for the duration of the total braking process. The highest speed at which an ATB intervened was at 133 km/h.

Results of the conducted analysis

As mentioned, only one brake long enough to be further investigated occurred. In §7.1.1 it was stated that the measurement frequency for the VIRM tribo trains was only 1/3 Hz. Therefore the progress of the friction coefficient cannot be sufficiently accurately be determined by the various traction installations/ED brakes; there is not enough measurement information available. Comparing the friction measured by the 3 traction installations/ED brakes is pointless because the measurement information to do so is inaccurate.

Figure 7.22 shows the friction coefficients measured by traction installation/ED brakes 1, 2 and 7 set off against the location where the friction coefficients was measured, for the emergency brake mentioned with a length over 200 meters. M_1 is de first, M_7 de middle and M_2 the last traction installation/ED brake. From figure 7.2.2 it cannot be concluded that the friction coefficient increases as a result of the magnetic track brake being activated. Therefore no conclusions can be drawn regarding the magnetic track brakes' roughing effect.

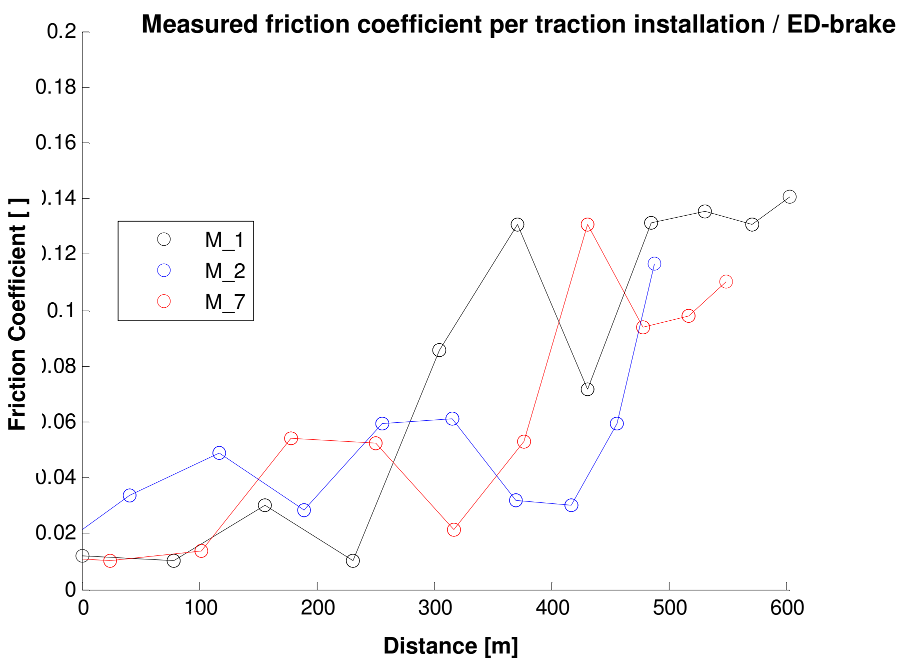

Figure 7.22 Friction coefficients for three traction installations/ED-brakes (tribometers) during an emergency brake on low adhesion

7.9.4 Conclusions effectiveness magnetic track brakes

In this paragraph an attempt has been made to answer research question 6 whether it is possible to assess the effectiveness of a situation-dependent measure (magnetic track brake). Regarding this research question the following has been concluded:

- Based on the research conducted it has been ascertained that no statement can be given on the roughing effect of the magnetic track brakes, due to:
    - The measuring frequency by the measuring trains was too low.
    - The number of emergency brakes of sufficient length where slipping occurred is too low.
- If the measuring frequency was increased and if measurements were conducted for a longer period and/or with more measuring trains it is expected that using the method mentioned insight could be obtained into the effect of the magnetic track brakes (or other situation dependent measures) on a slippery track.

This knowledge allows the question to be answered whether it makes sense to install magnetic track brakes on trains and if so how many. This insight can also contribute to the research into whether the braking system is adequate for a slippery track (see §7.3).

Remark
In reference [12] is given an optimization of the magnetic track brake. The current magnetic track brake works with a constant (maximum) magnetic force. If the magnetic force can be controlled depended on the circumstances it is possible to reduce the wear of the magnetic track brake and the growth of flakes (weld ons) on the magnetic track brake at unchanged roughening performance of the rail by the magnetic track brake.

7.10 Obtained insight; interpretation of all observations

The ultimate goal for the research conducted is to obtain the insight necessary for developing effective and efficient rules. §2.5.1 shows which knowledge is necessary for which solution. This paragraph will describe what the contribution was of the conducted research for the various solutions. Also it will describe which activities still need to be performed to be able to successfully implement the research direction.

7.10.1 Solving problems at the core

§2.5.1 shows that the solution ‘solving the problem at the core’ was left outside of the scope of this research because it is expected that the benefits of this measure will not outweigh the costs.

7.10.2 Measures to prevent the rail from becoming slippery

§2.5.1 shows that the necessary knowledge to develop measures that prevent the track from becoming slippery is to know what is where on the track. AdRem has not been able to answer this question. However, what has been ascertained is that low adhesion occurs at varying locations and times. These variations make it difficult/impossible to implement the right measures for all those locations. Therefore, it is unlikely that this solution (preventing the rail from becoming slippery) will be able to be interpreted efficiently and effectively.

7.10.3 Technical measures that can guarantee minimum braking and traction performance

In order to set up a safe train system and a reliable time schedule, reliable train performance is key. Braking and traction problems due to low adhesion are therefore not desired.

Guarantee minimum braking performance

The driving time loss found during braking can only be explained by the fact that drivers adjust their braking behaviour (justly or unjustly) to a situation of low adhesion. In order to ensure that they do not adjust their braking behaviour for (expected) low adhesion it is important that a driver can rely on a minimum braking deceleration.

It has been ascertained from past experience (red-signal passages) as well as during the measuring period that the safety risk for the VIRM train type in case of low adhesion is small. During the measuring period only one incident occurred where the braking deceleration was somewhat lower than required. From this, it can be concluded that the braking system is more or less adequate for braking in slippery circumstances. Therefore it is advised to re-do the research and conduct it more thoroughly to find out whether the remaining risk is indeed acceptably small. Before drivers are advised to rely on the VIRM braking system, the following also needs to be researched / realized:

- Investigate to what extent drivers can prevent safety risks thanks to their driving behaviour.
- Add extra functionality to the Automatic Ride Registration (black box) that can offer insight into the extent of adhesion (using the method of the VIRM tribo trains) prior to red-signal-passage due to low adhesion. Adding the functionality of the Automatic Ride Registration would offer the driver the option to prove that a red-signal-passage or collision was the result of low adhesion and not due to incorrect operation by the driver. Certainly if the driver is advised not to change his braking behaviour in view of possible low adhesion the driver cannot be blamed if he passes a red signal or collides as a result of low adhesion.

Should the abovementioned research show that the braking system is not safe in all low adhesion situations it is necessary to take additional steps. To which extent the location-dependent and situation-dependent measures are suitable for this purpose is further discussed below.

Location-dependent measure

As mentioned, in order to limit driving time loss by careful braking in potential low adhesion situations it is important that the driver can rely on a minimum braking deceleration. ProRail would like to take steps locally in order to ensure that a guaranteed minimum level of adhesion (adhesion standard) can be guaranteed for the total Dutch railroad network. Using location-dependent measures this appears to be impossible. Why this is not possible is further described below.

Determining where measures need to be taken will have to be done based on measurements or based on a prediction. As low adhesion can vary so emergencyly in time and can occur at varying locations a enormous amount of low adhesion measurements will need to be made or an accurate prediction model for low adhesion will need to be developed. At present, the knowledge into all parameters that affect low adhesion is insufficient to make accurate predictions. Conducting sufficient measurements is, if required, an option, for instance with ISAM, the VIRM tribo train method or by a further developed spectrometer. But this is where another problem arises, i.e.: after low adhesion has been predicted certain measures must be implemented within a limited amount of time. There is presently no location-dependent measure available that can meet these requirements at a reasonable cost.

Situation-dependent measure

Situation-dependent measures can be used to guarantee a minimum braking deceleration. The only uncertainty with these measures is: are they actually capable of guaranteeing the required minimum braking deceleration under all low adhesion circumstances. Until now only very limited information is available into whether the measures can actually guarantee a minimum braking deceleration. In order to obtain this insight it is advised to test the most obvious measures using the methods that were developed in the scope of this research.

An improved braking performance on a slippery track that does not lead to a guaranteed minimum braking deceleration is pointless as the driver still will not be able to rely on the braking system and will have to continue to brake carefully if low adhesion is suspected. Possible measures are: sandboxes and magnetic track brakes that are activated in cases of low adhesion.

Guarantee minimum traction performance

Braking has a safety function and that is why it is important that a certain minimum braking deceleration must be guaranteed. For acceleration a guaranteed minimum acceleration is not necessary. The more a minimum traction acceleration is realized, the larger the effect on driving on time percentage (punctuality).

As a guaranteed minimum traction acceleration is not necessary it will not be further discussed in this paragraph. In §1.6.5 improving traction performance is discussed when it is not necessary to guarantee the performance.

7.10.4 Warning the drivers

Presently the situation is such that drivers often brake carefully without necessity, because they unjustly think it is slippery. If this unnecessary braking could be prevented by a reliable warning system that would have a positive effect on driving on time (punctuality) during the fall season. However, a driver will only trust a warning system if it is 100% reliable. Below it will be shown why it is hard to create a 100% reliable warning system.

The information that a warning is based on will have to be supplied by measurements or by a prediction. As low adhesion can vary so fast in time and can occur at varying locations an enormous number of adhesion measurements will need to be made or an accurate prediction model for low adhesion will need to be developed. At present, the knowledge into all parameters that affect low adhesion is not enough to be able to make accurate predictions.

Conducting sufficient measurements is, if required, an option, for instance with ISAM, the VIRM tribo train method or by a further developed spectrometer. As low adhesion can in fact occur anywhere and can vary very fast in time (within 1 hour) it is paramount that a major part of the rolling stock is equipped with measuring devices. From a cost point of view, this presently does not seem like an interesting solution.

7.10.5 Technical measures that improve minimum braking and traction performance but do not guarantee it

Braking

As previously mentioned, in the present situation there is only a small risk that a VIRM train will pass a red signal. By taking technical measures that improve the braking performance but which the driver cannot rely on will improve safety a little bit more. Punctuality will not benefit because the driver will continue to drive cautiously because he will not know if the measure has been implemented. This solution will offer only limited benefits for braking and therefore it will not be further looked into.

Traction

It has been ascertained that a major part of the driving time loss is caused by traction during the first kilometre on a certain section. It was also ascertained that drivers influence the driving time loss by their driving behaviour. It is very possible that implementing measures without changing the drivers' behaviour will not lead to improved driving time because drivers will not use the measure as it is intended: to limit driving time loss it is advised to start by further investigating the drivers' behaviour in low adhesion situations. Why do drivers change their behaviour in case of low adhesion? If it can be proved that there is no sound reason why drivers drive differently in low adhesion situations, it would be advisable to determine what driving behaviour is desired and how drivers can be taught that type of driving behaviour.

Driving time loss during low adhesion situations is not only caused by the driver's driving behaviour but also because the wheels cannot transmit the required force to the track. For acceleration it is not important that minimum traction acceleration is guaranteed. Every extra time that a minimum traction performance is realized is a bonus. Below the pros and cons are stated for the location- and situation-dependent measures.

<u>Location-dependent measures</u>
Location-dependent measures are advantageous for situations where low adhesion often occurs in the same location. The most obvious location-dependent measures are: Sandite and shoulder management. The location-dependent measures can be optimized if they are only applied when it is slippery. An improved prediction model for low adhesion would be able to help here.

<u>Situation-dependent measures</u>
This research has ascertained that low adhesion can occur at varying times and locations. In order to be able to tackle as many cases as possible it is more obvious to take situation-dependent measures. This means that these measures must be implemented into all trains for which minimum acceleration performance is required. The following measures could be considered: improve traction control, sanders and more driven axles.

This research has shown that improving traction control would be an interesting solution. It was ascertained that the adhesion present during low adhesion is only limitedly utilized. On the other hand, the investment costs for this measure are relatively low because the necessary adaptations to the train are limited.

<u>Remark:</u>
It must be noted that in order to draw up a good cost/benefit analysis it is important to investigate the effectiveness of all interesting measures in order to be able to make a balanced choice.

7.11 Conclusions

Below a summary of the most important conclusions of this chapter can be found. The conclusions have been divided into separate parts with conclusions on the measuring method, the use of the measurement tool, the analysis methods and the obtained results.

Conclusions regarding measurement tool, use and analysis methods

- A method has been developed that enables monitoring the trains' performance on slippery track; in other words: making the problem of slippery track measurable was successfully achieved.
- Methods to test the effectiveness of the measures in daily practice have been developed.
- Based on the results it has been ascertained that it is necessary to look at the problem in a broader perspective than just the wheel-interlayer-rail. The drivers' behaviour also must be taken into account.
- Utilizing the diagnostic system in combination with GPS is a powerful tool for performance monitoring because information from many different parameters are available in the train; this way connections can be made between the various activities that take place in the train.
- By using the measurement tool (VIRM tribo train) combined with the elected measuring method and the analysis methods which were developed it was proved that the following research questions could be answered:
    - Risks of low adhesion to safety.
    - Effect of low adhesion on driving time.
    - Effect of driver's behaviour on the driving time in situations with low adhesion.
    - Where and when low adhesion occurs.
    - How fast low adhesion can vary in time and how much low adhesion can vary on consecutive stations.
    - Effectiveness of the measures.
- To answer most research questions it has been ascertained that it is not necessary to have an accurate insight into the extent of the low adhesion.
- Utilizing the diagnostic system for performance monitoring can also be used for a large number of other uses.

Conclusions regarding results

Based on the conducted measurement the following research results were obtained:

- Many more low adhesion situations occur during the fall season than beyond the fall; but also beyond the fall low adhesion with a high gravity occurs.
- Low adhesion can occur over lengths of tens of kilometres.

- There are locations (regions) where low adhesion occurs regularly; there are also locations (regions) where low adhesion seldom or never occurs.
- It was observed that if low adhesion occurs at a certain location, it generally occurs on the outgoing and incoming track.
- Extreme low adhesion can occur very emergencyly (within an hour) in time.
- A reasonable case was made for the fact that low adhesion plays an important part in the dip on driving on time during the fall.
- During the measuring period, the braking system on the VIRM rolling stock proved to adequately prevent peaks caused by low adhesion. For VIRM rolling stock low adhesion is a low safety risk.
- The driving time loss in the fall is caused for approximately ¾ during the first kilometre of a route during acceleration and approximately ¼ during the final kilometre of a route during the braking process.
- In the fall slippery stations cause substantial driving time loss. On a slippery route (<10 km) the driving time loss due to low adhesion can amount to approximately 2 minutes.
- Drivers change their driving behaviour on a slippery track during braking as well as during acceleration and therefore they influence the driving time (punctuality). If research is conducted into applying the measures to reduce inconvenience caused by low adhesion the driver's behaviour must be taken into account.
- The existing prediction model for low adhesion is only suited to send an alertness warning. It is not good enough to be able to reliably warn drivers or to take measures based on the warning.
- Mainly for the traction steering and to a lesser extent for the ABI there is a lot of room for improvement to utilize the friction already present. This could greatly improve the traction and braking performances.
- Sandite does not work such that after applying it no low adhesion will occur during the rest of the day. On approximately half of all days Sandite is applied for no reason.
- It was not possible to obtain insight into the effectiveness of magnetic track brakes.

Remark

The results stated were based on research with a VIRM. Other rolling stock could lead to a different outcome.

7.12 Evaluating the measuring system, test setup and analysis method

7.12.1 The measuring system

The philosophy behind the measuring system is that it enables many adhesion measurements; that the accuracy of the measurement system is not very accurate is accepted. Another important aspect was that the measuring system could be able to supply, in addition to low adhesion, other measurement information thus enabling relations to be made between low adhesion and location, date and time, driver's behaviour and using the magnetic track brake. Both aspects have been greatly valuable for this research.

It was too bad that the measuring system's sample frequency was only 1/3 Hz. Therefore, it was not possible to obtain insight into the effect of the magnetic track brakes.

The fact that measurements can only be conducted when a wheel slip occurs did not prove to be a problem. The reason for this is that this research did not in fact aim at determining the extent of low adhesion but at determining the consequences of the low adhesion (performance monitoring) on for instance the traction performance, driving time, driver's behaviour, etc.

7.12.2 Test setup

It was known in advance (especially from drivers) that low adhesion could vary a lot from location to location and from moment to moment. In order to determine if this variation actually does take place, it would be necessary to conduct a lot of measurements at different times of day at the same location and at the same time of day at different locations. For this reason the VIRM tribo trains were deployed during the fall as much as possible on one route (Den Helder-Nijmegen) so that on that route various measurements could be conducted per day. This proved to be a good choice. That is why insight was obtained into the variation of low adhesion at a certain location during the day, but also the differences in low adhesion in sections of the route on the same day.

The test setup of choice to show the effectiveness of Sandite was not adequate. In order to be adequate more VIRM tribo trains per day will have to pass the test stations. Moreover, the choice for the test and reference track also proved to be unsuitable.

A strong point of the test setup was that not only information on low adhesion was stored but also information of the situation when it was not slippery. This is important in determining whether the low adhesion measured was structural or incidental.

7.12.3 Analysis methods

The analysis methods are initially aimed at finding out whether it is possible to answer the research questions. It was ascertained that not all research questions were actually answered, but it was established that by making adjustments to the methods developed it would be possible to answer all research questions. These adjustments relate to sample frequency, the number of train passages at a location and the correct choice for a test and reference station.

It must be noted that making algorithms for the analysis methods is labour intensive. If a similar research is conducted again, a large part of the work has already been done because the existing algorithms can be re-used.

7.12.4 General

Because the trains drove the route Den Helder-Nijmegen as much as possible during the fall, the results predominantly relate to that route. If it were required to obtain insight into other routes, a similar research would need to be conducted for those routes. If a higher level of accuracy of the results is required, it would be advised to conduct this research for a longer period of time or with more measuring trains.

7.12.5 Conclusions

Regarding the measuring system, the test setup and the analysis method the following conclusions can be drawn:

1. The measuring method with the VIRM tribo trains works. It is a powerful instrument in obtaining insight into low adhesion.
2. The first measuring system that can measure low adhesion on a large scale from a passenger train running in service and in addition can make connections between operation and low adhesion.
3. Considering the large number of insights that have been obtained (see the results of chapter 7) it can be said that the VIRM tribo train is a workable measuring system to acquire knowledge on the current low adhesion.

<u>Remark</u>
This research was conducted with the measurement information of the VIRM trains. Therefore, the results do not automatically apply to other rolling stock. The older rolling stock is probably more sensitive to low adhesion because the traction installations, traction control but also the braking system and the WSP perform less well with low adhesion.

7.13 Other applications for performance monitoring

This research showed that performance monitoring has offered significant insight into the problem of low adhesion. Performance monitoring using the diagnosis system can be utilised for other subjects also, such as:

- Maintenance optimization. How often are various parts of a train used and how often does a (technical) malfunction happen.
- Analyse drivers' driving behaviour for energy-saving purposes.
- Establish a train's occupancy rate.
- Insight into door and toilet use.
- Monitor the voltage of the overhead cables.
- Show that using track conditioners such as flange lubricants and friction improvers is safe.

8 Interim developments

At the start of the research project AdRem it appeared that knowledge on slippery tracks is predominantly based on subjective observations. In order to acquire insight into the problem by using objective measurements the VIRM tribo train was developed. During the research period other measurement methods were also developed. In §8.1 through §8.5 these measurement methods will be described. Another development that occurred in The Netherlands during the research project is the fact that ProRail not only wishes to reduce the problem of slippery tracks but also wants to reduce the problem of tracks that have a too high level of adhesion in curves. §8.6 discusses this problem in further detail.

8.1 Simple slider

Within the scope of the AdRem research program the chair Surface Technology and Tribology at the University of Twente developed a measurement tool to measure low adhesion that works by the principle of simple sliding (see reference [32]). The simple slider works with a metal block that presses down on the rail. When the train starts to ride the block slides over the rail (see figure 8.1). The force with which the block is pressed down onto the rail (normal force) and the force required to move the block along the rail (forward force) is measured. The level of adhesion of the track is lower, as the forward force is lower when a certain normal force is applied.

The simple slider was developed to obtain insight into the extent of low adhesion of the track under varying circumstances. Also, the experience of developing the simple slider turned out to be very useful for the tribo tester developed by the university (see §8.2). The simple slider enables low adhesion to be measured non-stop. Disadvantages are the susceptibility for abrasion and the heat development during prolonged use.

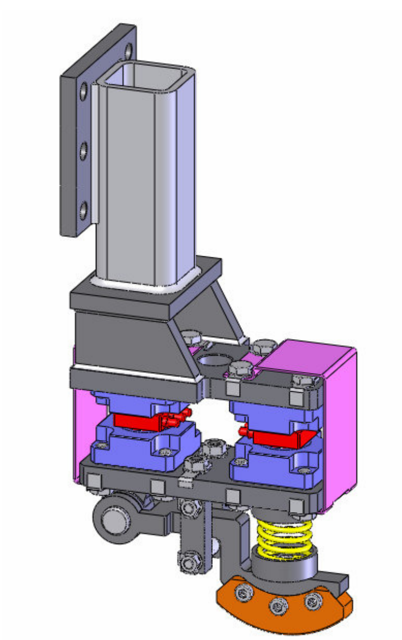

Figure 8.1 Drawing of the simple slider

8.2 Tribo tester University of Twente

The chair Surface Technology and Tribology of the University of Twente developed a tribo meter that can measure traction curves up to a velocity of approximately 90 km/h. The measurement method and functionalities are similar to the tribo testers as mentioned in §4.6. The tribo tester (see figure 8.2 and 8.3) was developed to gain insight into the characteristics of the intermediate layers as they occur in daily life. In order to get this insight, the tribo tester was installed on a special test train. Measurements were conducted on the route Utrecht-Deventer-Zwolle-Utrecht on the line Rotterdam-Hoek van Holland and on the line Rotterdam-Vlissingen, both in the fall as well as beyond fall.

The major advantage of the tribo meter is that it can measure traction curves non-stop. A disadvantage is that the device is so complex it cannot be installed on a passenger train in service for safety reasons. More information can be found in reference [33].

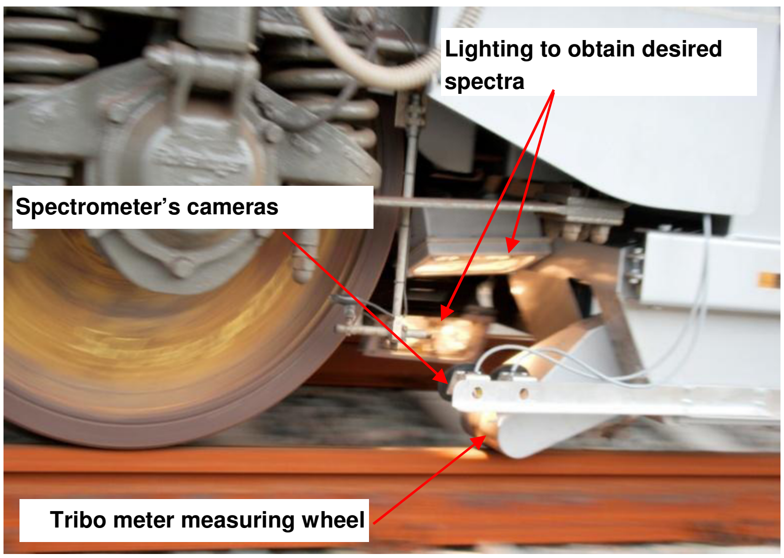

Figure 8.2 UT tribo tester and spectrometer installed in the test train.

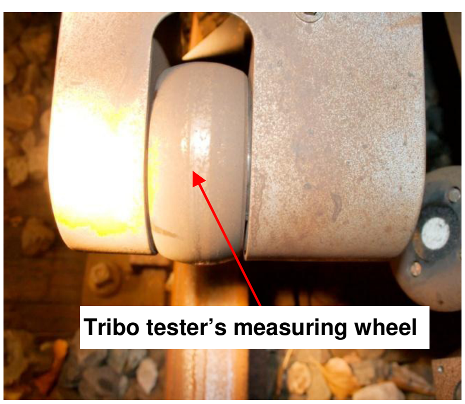

Figure 8.3 The tribo tester's measuring wheel developed by University of Twente.

8.3 Spectrometer Wageningen University

§2.5 mentions that it would be advisable to know which substance can be found on the track. In order to get insight into this aspect the plant physiology department at Wageningen University developed a spectrometer on a test train. A spectrometer is a measurement tool that, based on the spectrum of the reflected light, deriving from a certain substance, can determine which materials the substance is made up of. Spectrometry is an interesting measurement method because it takes place without actual contact with the rail. In addition it is interesting because it can detect possible contamination before low adhesion is caused due to moisture (due, fog, light rain, etc).

Based on the results of the spectra-measurements preventive measures could be taken. In order to establish how slippery a detected intermediate layer is, the tribo tester of the University of Twente (see §8.2) was installed in the same test train (see figure 8.2).

References [34] and [35] describe how it works, how the test was set-up and the results achieved. Due to flaws in the test set-up determining which substance was present on the track was not successful. The research conducted, however, did show that spectrometry is an interesting method when it comes to gaining insight into which substances can be found on the track.

8.4 ISAM

Based on AdRem accomplishments, the Lloyd's Register Rail and the OPM (Design, Production and Management) department of the University of Twente developed a concept for a tribo meter called ISAM (In Service Adhesion Monitoring). This measurement tool determines the extent of low adhesion based on the angle of inclination of the straight part of the traction curve (see figure 3.1). In order to determine the angle of inclination it is necessary to determine the measuring wheel's forward force (tangential force), vertical force (normal force) and slipping velocity. In order to determine the slipping velocity it is important to be able to very accurately determine the forward speed of the train and the rotation speed of the wheels in question. A description of the system in further detail can be found in reference [36].

The advantage of this concept is that the friction can be measured non-stop from a passenger train running in service. During measuring no extra friction or heat development occurs. In addition it is a relatively inexpensive measurement tool. Disadvantage of the measurement tool is that no proof of principle has been performed that proves that the method will actually work.

8.5 Tribometer by the Loughborough University

Dynamic behaviour of the bogie changes depending on the adhesion between the wheel and the rail. Braking, acceleration and conduct forces have the same force generation mechanisms; creep forces in the wheel/rail contact. These generation mechanisms for the braking and acceleration forces are also used by ISAM.

Loughborough University investigated whether it is possible to predict adhesion based on the dynamic behaviour of the bogie. Insight into the bogie's dynamic behaviour is acquired by acceleration sensors on the bogie, which can determine the forces and torques that the track apply to the wheels. Based on models created and a proof of principle that was performed it has been proven that it is possible to get an indication of the extent of adhesion based on dynamic behaviour. More information on this research can be found in reference [37].

8.6 Problem of track with a too high level of adhesion

Not only slippery track lead to problems. Track with a too high level of adhesion in curves can lead to rolling contact fatigues (cracks in the rail) and to squeal noise in curves or in switches. This is caused by the fact that the right and the left wheel are connected by a rigid axle resulting in extra slipping in curves between the wheel and the rail. Repairing the cracks is expensive and the squeal noise leads to noise pollution, which is mainly a nuisance for the people living in the neighbourhood.

In order to reduce the friction in curves or switches a friction modifier (lubricant) is applied to the top of the rail. The lubricant is supposed to reduce friction, but not to the extent that the desired braking and acceleration forces can no longer be transmitted. In daily life it has however been proven that the applied amount is very determinative for the effect. If too little is applied there is no effect whatsoever, if too much is applied low adhesion occurs.

The knowledge acquired by the AdRem project, more specifically the measurement methods, can be used to reduce the problem of track with a too high level of adhesion. Using the developed measurement tools unsafe situations can be detected and also they can help determine which dosis needs to be applied. It is recommended to tackle the problem of tracks that are too slippery and too rough integrally.

9 Policy advice

This research's ultimate goal is to offer advice on how the problem can be reduced. This chapter will offer the advice based on the research.

9.1 Measures

As low adhesion can vary in time and location it is advisable to take measures that are flexible. For instance sanders, magnetic track brakes, installing more driven axes.

Regarding the effectiveness of the measures the magnetic track brakes, sanders, Sandite, installing more driven axes and improved traction control are expected to be most effective. Therefore these measures are discussed below. Should the aforementioned measures not offer the desired results it is advisable to further investigate the measures already developed. It is noted that the WSP's on the Dutch rolling stock have been optimized in recent years. Therefore, this subject will not be further discussed here.

Sandite
Sandite has been applied for over 10 years, but until now it is still not known how effective Sandite is; how many trains (axle passages) benefit from it. That is why it is advised to show its effectiveness with the method developed (see §7.8). Should this research show that the gains outweigh the costs it is advisable to take the following further steps.

1. Using the VIRM tribo trains to further investigate which stations should treat using Sandite. For this it is necessary to know where and when and to what extent is slippery in The Netherlands.
2. Momentarily stations are often treated with Sandite even though it is not slippery on that given day or in that given location. In order to increase the efficiency of the Sandite campaign it is advisable to apply Sandite based on predictions. This requires that the predictions must be improved. The quality of the prediction must be increased and must differentiate between regions. In order to improve the prediction model the prediction can be tested in comparison to the measurement conducted by the VIRM tribo trains. This creates feedback loop.
3. An additional functionality can be added to the existing Sandite campaign (preventive nature). Where low adhesion (slipperiness) is detected (for example with VIRM tribotrein) Sandite is applied (reactive).

Magnetic track brakes
Whenever considering new rolling stock the discussion re-occurs whether it must be equipped with magnetic track brakes. Basic reasons for this discussion is that it is not certain what the magnetic track brakes contribute to the braking performance on a slippery rail. That is why it is advisable to show the effectiveness of magnetic track brakes using the method mentioned in §7.9.

Sanders
The large advantage of sanders is that they are effective during braking as well as during acceleration. What can be said about magnetic track brakes also applies to sanders: it is uncertain what the effectiveness is. It is advised to show effectiveness using the method

mentioned in §7.9. Based on that method insight can be obtained into the benefits that sanders offer. Based on costs and gains it can be decided whether or not it is a wise investment. If a certain minimum effect is proved this method can also be used to determine the minimum amount of sand that needs to be applied per meter rail in order to be able to guarantee the required train performance.

Improving traction control

Considering the fact that a large amount of time is lost during acceleration on slippery tracks it is advisable to investigate whether it is possible to optimize the existing traction control in order to be able to utilize the friction at hand better. It is advisable to conduct market research into the products offered by various suppliers that are already available on the market. The market research should indicate which improvements regarding the traction performance could be expected with the various products. This research should be conducted for each separate type of rolling stock.

If the preliminary research indicates that there are products available that probably will help improve the traction performance, it would be advisable to conduct a test to prove so. It is advisable to use the method described in §6.3 to do so. If the test shows a positive result that should lead to a situation where the gains easily outweigh the costs because in all due probability the change would be a software change.

More driven axes

It was proved that a large amount of time was lost during acceleration on a slippery track. The VIRM trains have relatively few driven axes compared to their total number of available axes. This causes the VIRM to need a relatively high level of adhesion between wheels and rail in order to achieve a traction performance. In addition to an improved traction performance, choosing for more driven axes would offer more advantages: reduced abrasion of the wheel surface, reduced wear of brake parts susceptible to wear and tear, capability to return more energy to the overhead cable. It is advisable to investigate whether the advantages outweigh a possible disadvantage: more traction systems will lead to increased maintenance costs.

9.2 Safety

This research shows that the safety risks for VIRM on a slippery track are low. It is advisable to further investigate (by using the VIRM tribo train method) if this indeed is the case; more measuring trains and a longer period during which measurements are conducted. If this is actually the case it will mean that the VIRM braking system is adequate to brake safely on a slippery track. That also clarifies which measures need to be taken for other rolling stock. This would also mean that drivers no longer need to brake carefully during the fall season because of possible low adhesion.

At present, a number of developments are taking place which require that the braking performance of the various types of rolling stock are known; especially the peaks in the braking distance. This concerns: ERTMS, increasing the train speed to 160 km/h, high frequency tracks (12 trains per direction per hour) and reducing signal distances. Knowing what the braking distance is and especially knowing what the peaks are in the braking distance is important if the track capacity, which in The Netherlands is limited, is to be optimally utilized. It is advised to monitor the braking distances of the various types of rolling stock and to try to obtain as much insight as possible into the causes for braking distance extensions. An option is to use the diagnosis system for this purpose.

9.3 Driving on time

This research has shown that ¾ of the loss of driving time occurs during the first kilometre of acceleration. The other quarter of loss of driving time occurs to a large extent when braking to enter a train station. If reducing the influence of low adhesion on punctuality (driving on time) is desired, improving traction performance will offer the best results. Possible steps to improve the traction performance are: improving traction control, installing more driven axes, sanders and possibly also Sandite. It was proved that the drivers' behaviour not only influences the braking process but also influences the acceleration process. This is explained in further detail in §9.4.

9.4 Driver's behaviour

Braking

If it appears that the VIRM braking system is adequate, and if it appears that the drivers careful driving behaviour for expected low adhesion does not contribute to reducing the safety risk, drivers can be advised to no longer adjust their driving behaviour in the VIRM trains during low adhesion.

At present the driver is responsible for a red signal passage caused by low adhesion. Preventing a red signal passage therefore is higher on a driver's priority list than driving on time. If it is required that he no longer adjusts his driving behaviour to low adhesion he no longer can be held responsible for red signal passages due to low adhesion (if this should occur despite thorough investigation). A driver therefore must be able to show that prior to the red signal passage low adhesion had occurred. In order to achieve this, it is advised to expand the Automatic Ride Registration (the train's black box) with the low adhesion detection functionality used in the VIRM tribo trains.

Acceleration

It was proved that drivers adjust their handling to suit the circumstances during acceleration on a slippery track. It is advised to investigate why drivers adjust their acceleration behaviour in low adhesion situations. It is also advised to investigate if the VIRM trains are sufficiently equipped if a wheel slip occurs to prevent damage to the train. It is advised to conduct an investigation into this aspect also with rolling stock that is equipped with a less advanced traction system.

If it is shown that it is not necessary to reduce the level of traction during low adhesion situations it is advisable to teach drivers the required traction behaviour (this is a relatively inexpensive measure because it requires no large investments in technical measures).

9.5 Rail conditioning

ProRail intends to apply friction modifier in curves (a lubricant with special characteristics) in order to prevent squeal noise and cracks in the rails. It appears that applying too much friction modifier at switches in train yards makes the track slippery and when not enough material is applied there is no effect to be found. Apparently applying just the right dosage is the key. In order to apply the right dosage it is necessary to have a measurement tool that is sufficiently accurate and that can make measurements even if no wheel slip occurs. The VIRM tribo trains do not meet this requirement.

Establishing the correct dose within the scope of this research can best be conducted with the stationary tribometer (see §4.7) because in that case for each train passage with a measurement system the adhesion can be determined locally.

If friction modifiers are to be used in practice then it would be advisable to install a measurement tool in the application train that can assess the extent of roughness/slipperiness and based on the assessment can decide if friction modifier needs to be re-applied. A measurement system capable of doing this is the ISAM (see §8.4). For the research into rail conditioning, it is advisable to conduct a feasibility study into the stationary tribo meter and ISAM.

9.6 Better understanding

In order to effectively take steps and/or improve prediction for low adhesion it remains necessary to have more knowledge available on the problem of low adhesion. It is therefore advisable to further investigate:

- What is where on the track.
- Where and when is it slippery.
- Under which circumstances does it become slippery.

What is where on the rails
For AdRem Wageningen University studied to see if it was possible to determine via spectrometry what is on the track (see §8.3 and reference [34] and [35]). This knowledge is important in determining which methods would be most effective in preventing a certain type of low adhesion. This research has not yet shown whether this is possible. It is advisable to conduct further research into this subject.

Where and when is it slippery? And to what extent?
In order to be able to know where low adhesion occurs, and take steps based on that, it is required to have a better insight into where and when it is slippery and to what extent. It is advisable to monitor low adhesion throughout The Netherlands for a period of at least one year. A possibility is to use the principle of the VIRM tribotrain. Important for monitoring the whole country is to use enough measuring trains.

Under what circumstances does it become slippery?
In order to effectively take steps and/or improve prediction for low adhesion it is important to know which parameter influence low adhesion and to what extent. The most effective way of doing this is by location monitoring. At one or more slippery locations a stationary tribo meter (see §4.7) is used during each train passage. Also, the circumstances on location, such as leaves on the track, temperature of the location, dew temperature, wind velocity, wind direction, track spectrum, humidity, should be monitored. It is advisable to conduct a test on location that is known for low adhesion during the fall season and on a location that is known for low adhesion as a result of industrial pollution.

9.7 Data management

Year after year the availability of information increases. This research is an example of how information already available can offer insight into a certain problem. It is advisable to use data management more efficiently in future:

- Determine which part of the organisation/departments need which information.
- Determine which information is readily available.
- Determine which information is desired/demanded but is not yet available and investigate how to obtain that information.
- Creating a data warehouse (storage system) for all data.

As data analyse is time consuming it is advisable to develop a universal data-analysis tool.

9.8 Specification for new rolling stock

In this chapter it was shown that adjustments to the rolling stock could reduce the problem. When specifying new rolling stock it is advised to take the following considerations into account:

- How many driven axes are required to offer the required acceleration performance?
- How many magnetic track brakes are necessary to prevent peaks in the braking distance from occurring?
- Is it necessary to equip trains with sanders to obtain the required acceleration performance and to prevent peaks in the braking distance from occurring?
- Is it desired to expand the Automatic Ride Registration system with the functionality used in VIRM tribo trains?
- Which functionalities must the diagnosis system possess?
- Is it desired to equip all trains with an on board – land – connection?

9.9 Initiate a EU research project

This chapter offers a list of recommendations. In order to conduct these recommendations will require a large investment. Especially testing the measures will lead to high costs. As countries abroad also encounter the same problems it is advisable to collaborate with foreign parties (train operating companies, infrastructure managers, suppliers, Adhesion Working Group, UIC, etc.). The following strategy could be followed:

- Draw up a plan of approach.
- Investigate subsidy options.
- Contact foreign parties.

10 Evaluation of the research

Starting situation

At the start of the research the situation as depicted in figure 10.1 existed. In that situation there was only limited knowledge on how the problem of low adhesion worked in practice. Basic knowledge regarding low adhesion was limited such as: where and when is it slippery and to what extent, how does the driver operate a train during low adhesion situations. The knowledge that was available was mainly based on the drivers' subjective observations. Another area where limited knowledge was available was the effectiveness of the applied measures to combat low adhesion. Due to a lack of insight into the effectiveness it was also difficult to make a cost/benefit decision. The question whether or not is is wise to invest in measures is therefore impossible to answer. It is also difficult/impossible to optimize existing measures.

Due to the absence of this basic knowledge it was not possible in the past to develop effective and efficient measures. If the problem cannot be measured it also cannot be determined whether or not a measure had any effect. The goal for this research can be summed up as gaining (measurable) insight into the problem and formulating suggestions for improvement based on that insight.

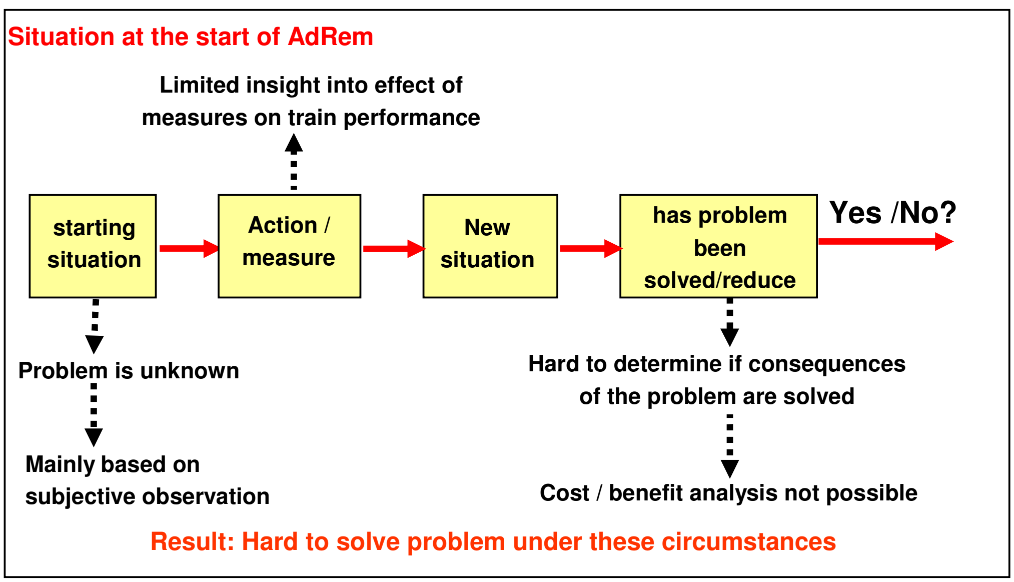

Figure 10.1 General presentation of the low adhesion problem – situation at the start of AdRem.

Methods for gaining insight

In order to be able to obtain the required insight it was necessary to develop a measurement method (measurement tool, set up and analysis method) that can determine how the problem occurs in practice and what the effectiveness of the measures is in practice. By choosing the diagnosis system as the foundation for the measurement method it was possible to have a large number of parameters available and to conduct a large number of measurements during normal train service hours at relatively low costs.

Obtain results

A measurement train was successfully developed that is capable of measuring low adhesion, but which can also make a relation between low adhesion and location, time, traction and braking performances, driving time, drivers' behaviour and measures taken. Analysis algorithms were developed to process the measurement information. In general the following insights were obtained:

- Quality of the VIRM braking system on a slippery track.
- Where and when low adhesion occurs.
- Speed at which low adhesion can vary in time.
- Influence of low adhesion on driving time/ driving on time (punctuality).
- Cause of loss of driving team during the fall season.
- Driver's driving behaviour (both during acceleration as well as braking) on a slippery track.
- Effectiveness of the traction control and WSP.
- Quality of the predicting model for low adhesion.

The research was only limitedly successful at obtaining insight into the effectiveness of the measures taken (Sandite and magnetic track brakes). Based on the research conducted into effectiveness of the measures a lot of room for improvement has been detected regarding the testing method. It is expected that the improved methods will offer insight into the effectiveness of the measures taken.

Situation at end of AdRem

Thanks to the measurement system developed, the depicted starting situation in figure 10.2 could be determined by an objective measurement. It is possible to determine how the problem occurs in practice. Because insight into the situation has been obtained it is possible to detect possibilities for improvement. If subsequently the improving measures are applied a new situation is created. For this new situation it is also possible to determine how large the problem is. It can be determined whether or not the problem is reduced/solved. If the trouble has not diminished sufficiently additional steps can be taken. In summary: by monitoring performance in the manner described above the problem can be reduced/solved in a purposeful manner. A feedback loop has been created.

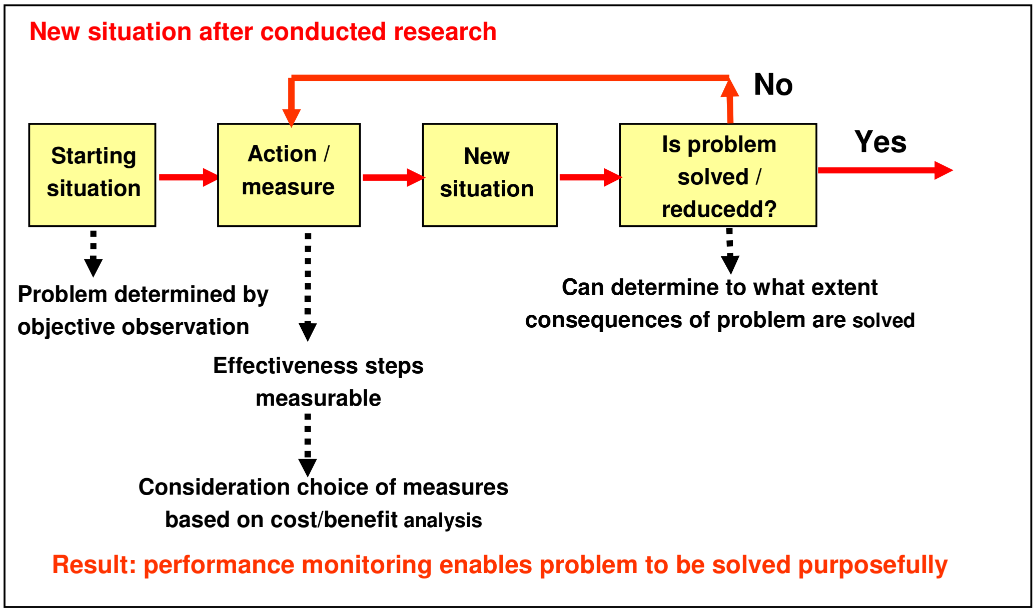

Figure 10.2 General presentation of the low adhesion problem – situation after AdRem.

In order to be able to obtain insight into the effectiveness of the measures in practice in view of this research a testing method was developed. Whether this method works has not yet been proven. It is expected that the developed testing method will be able to offer insight into the effectiveness of the measures taken. If the effectiveness of a measure can be assessed it is also possible to optimize it because the effect of an improvement can be established.

In conclusion

Monitoring the performance during low adhesion has led to increased insight of the problem. The insights are now based on objective measurements instead of on subjective observations. These insights have lead to a large amount of advice on how to reduce the problems caused by low adhesion.

For this research it was important whether and if so how to obtain the desired insight. It has shown that a large number of the developed methods to obtain insight actually work.

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Nawoord

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Niels van Steenis

Assen, mei 2010

Appendix A Maps of low adhesion events

Figure A1 through A6 show low adhesion events in a map of the Netherlands. The colours show the gravity of an event.

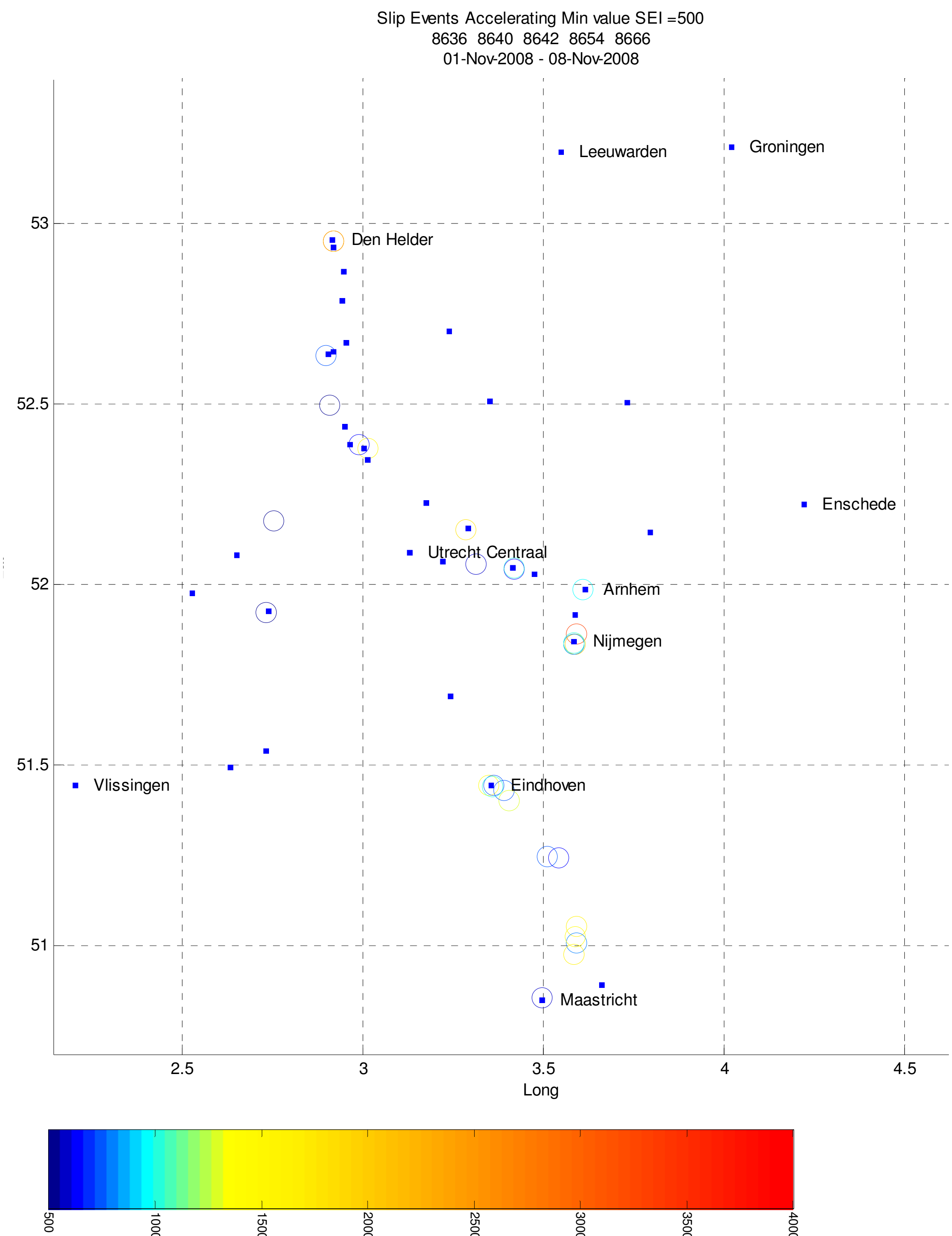


Figure A1 Low adhesion in case of acceleration (traction); November 1 through 7, 2008.

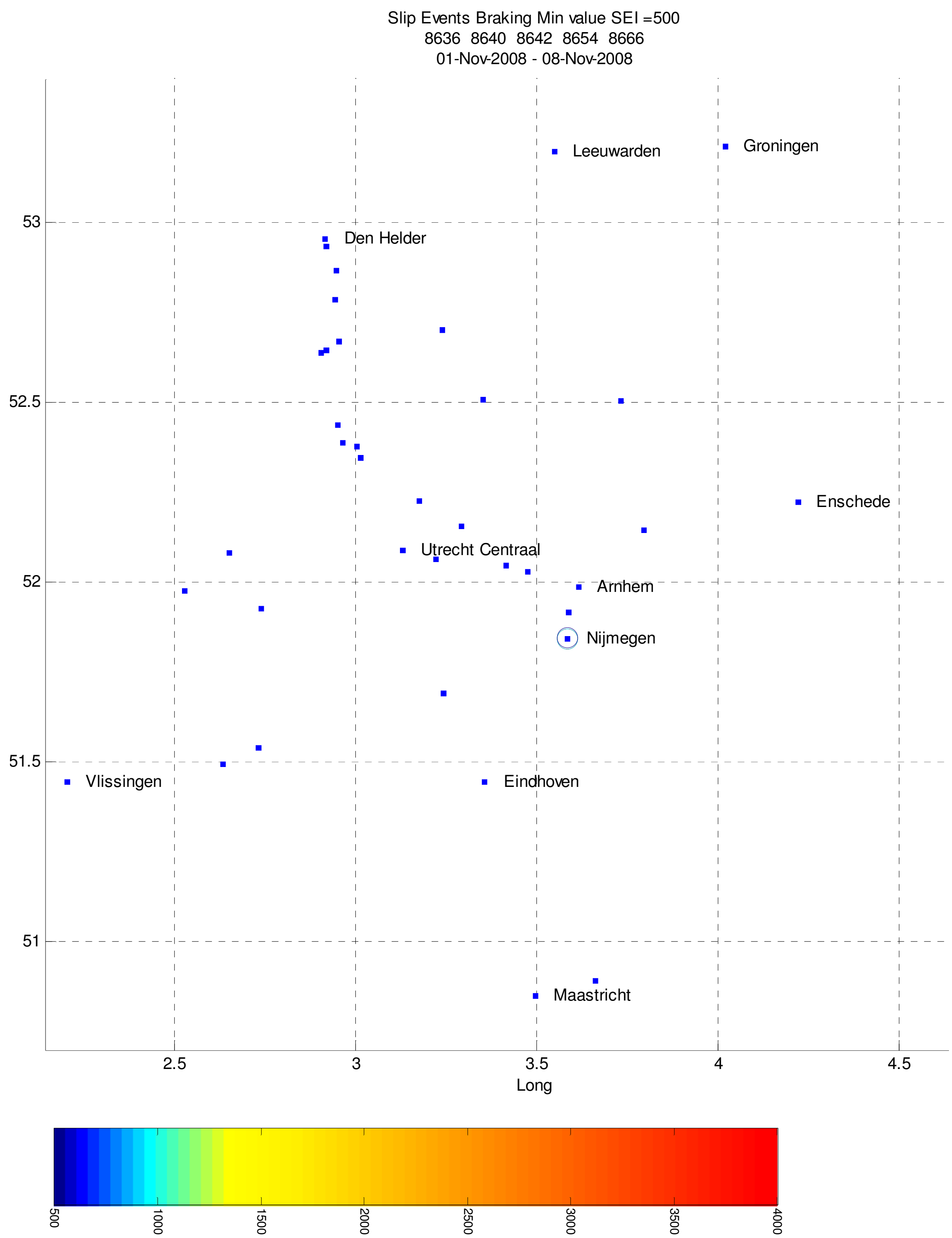


Figure A2 Low adhesion in case of braking; November 1 through 7, 2008.

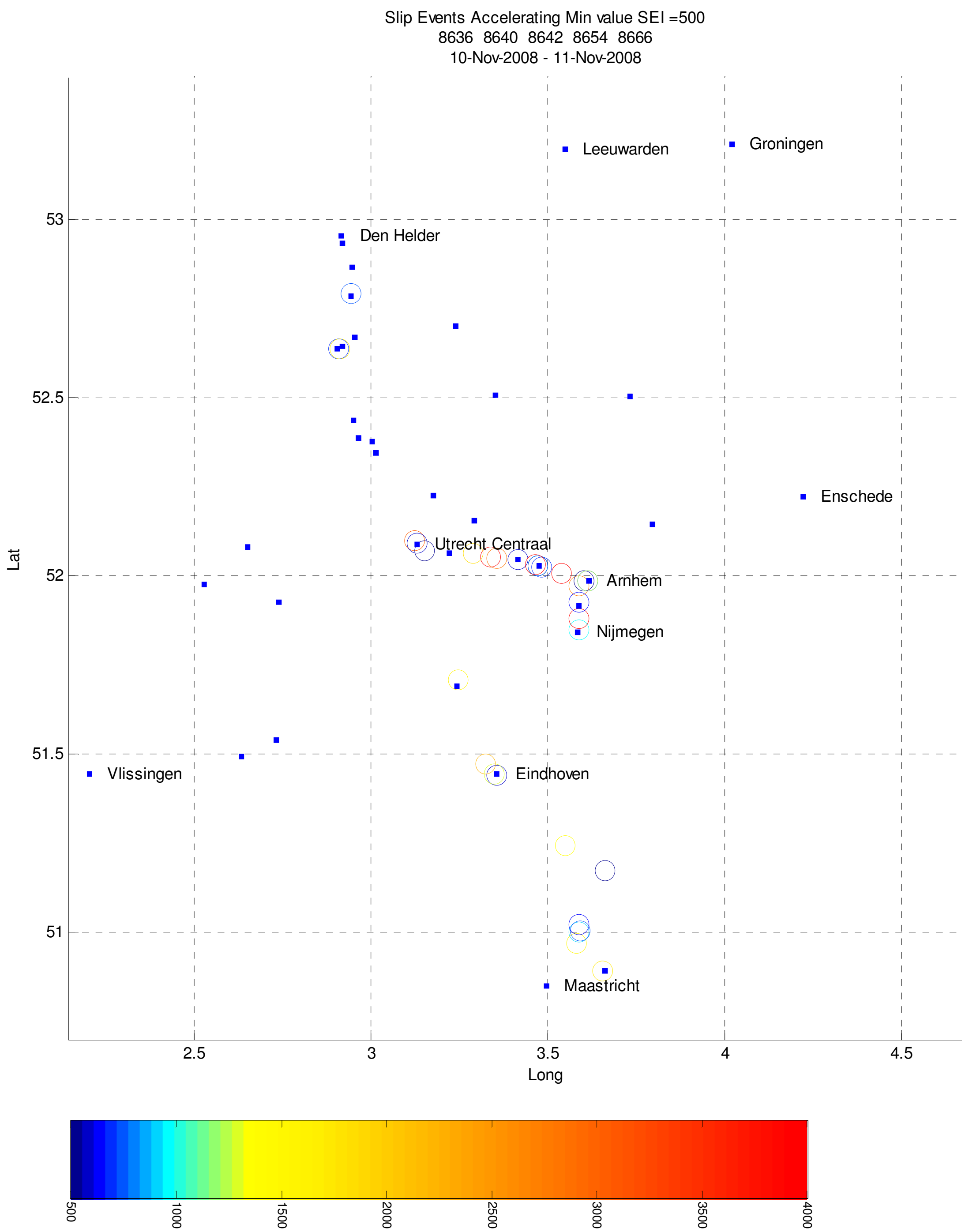


Figure A3 Low adhesion in case of acceleration (traction); November 10, 2008.

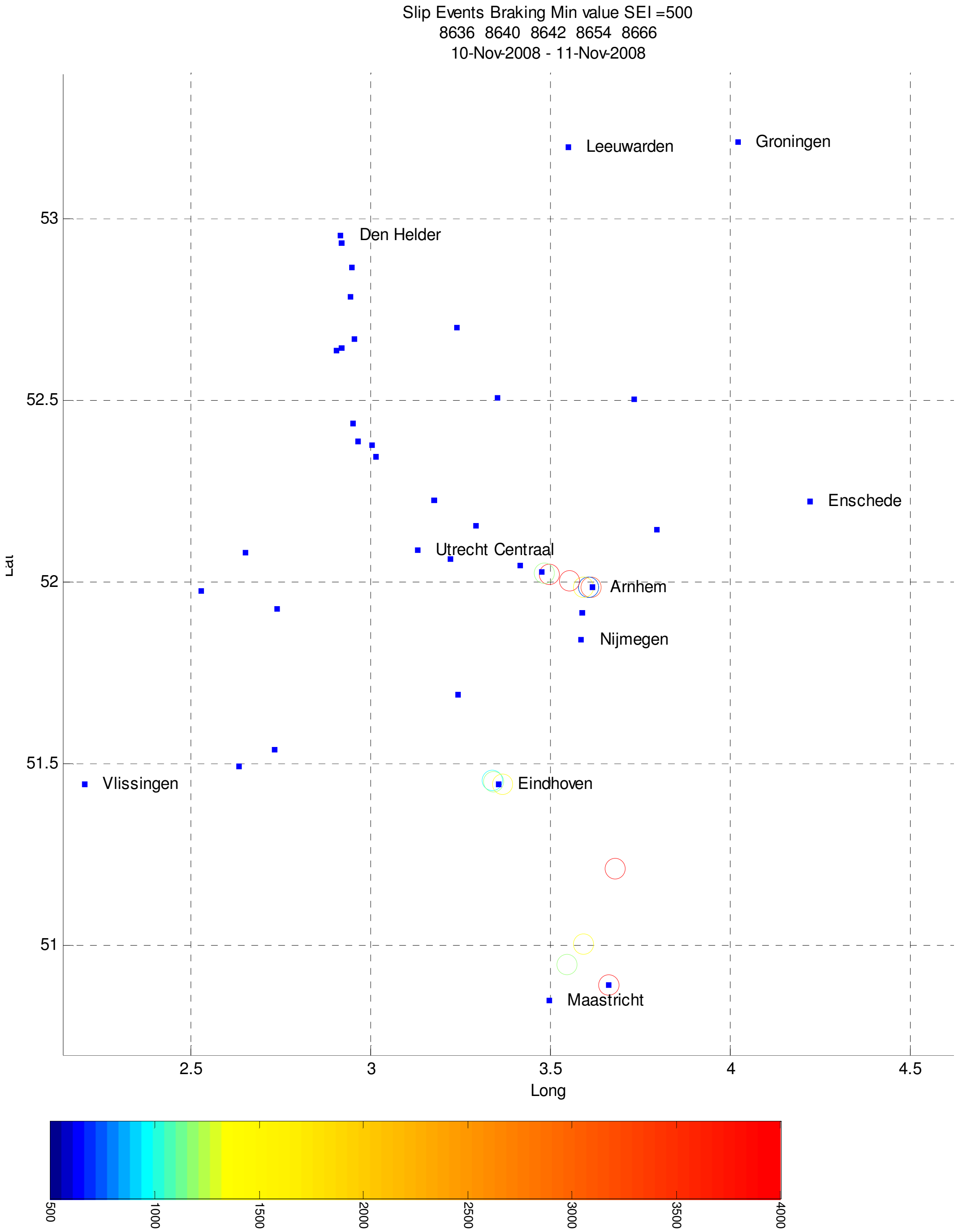


Figure A4 Low adhesion in case of braking; November 10, 2008.

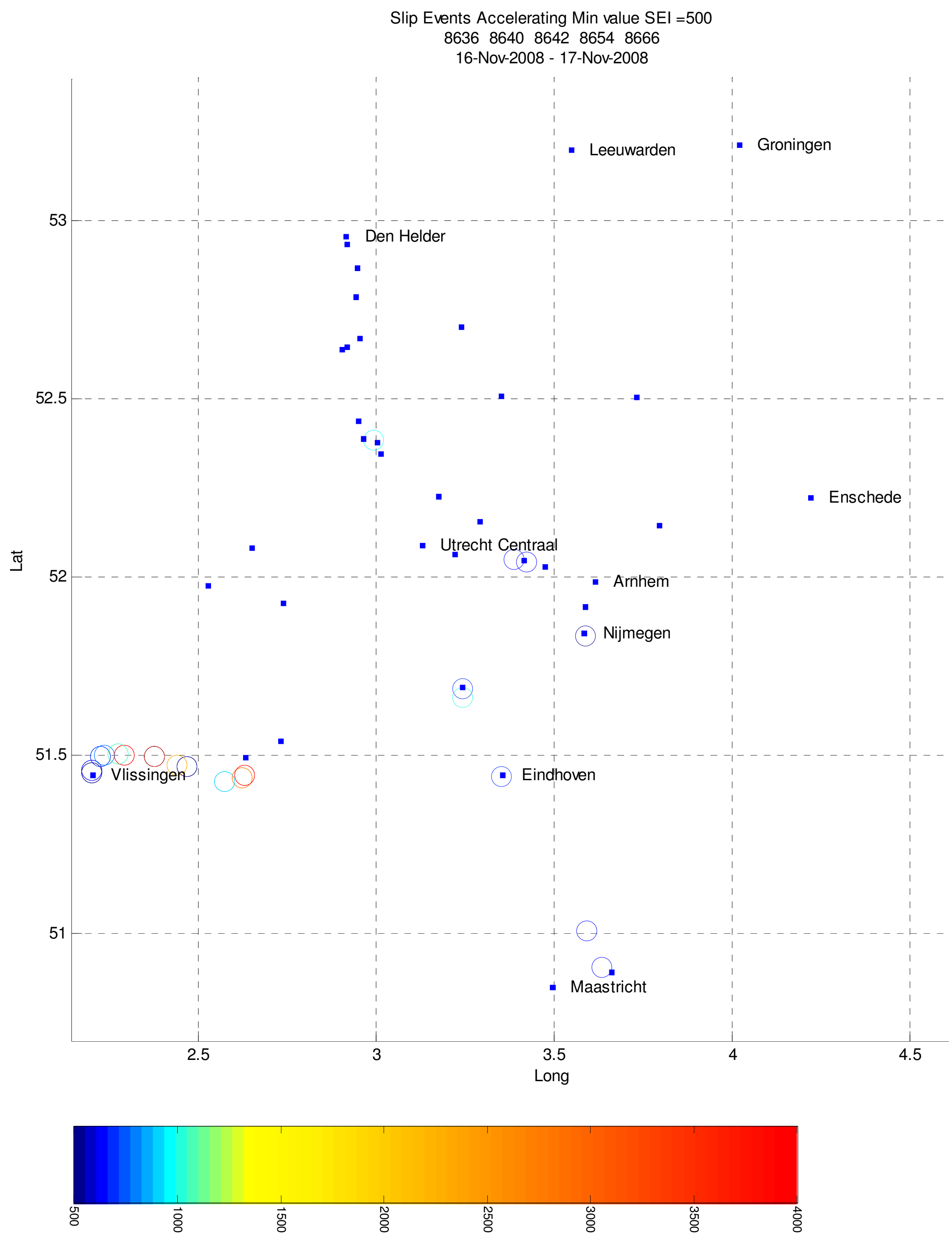


Figure A5 Low adhesion in case of acceleration (traction); November 16, 2008.

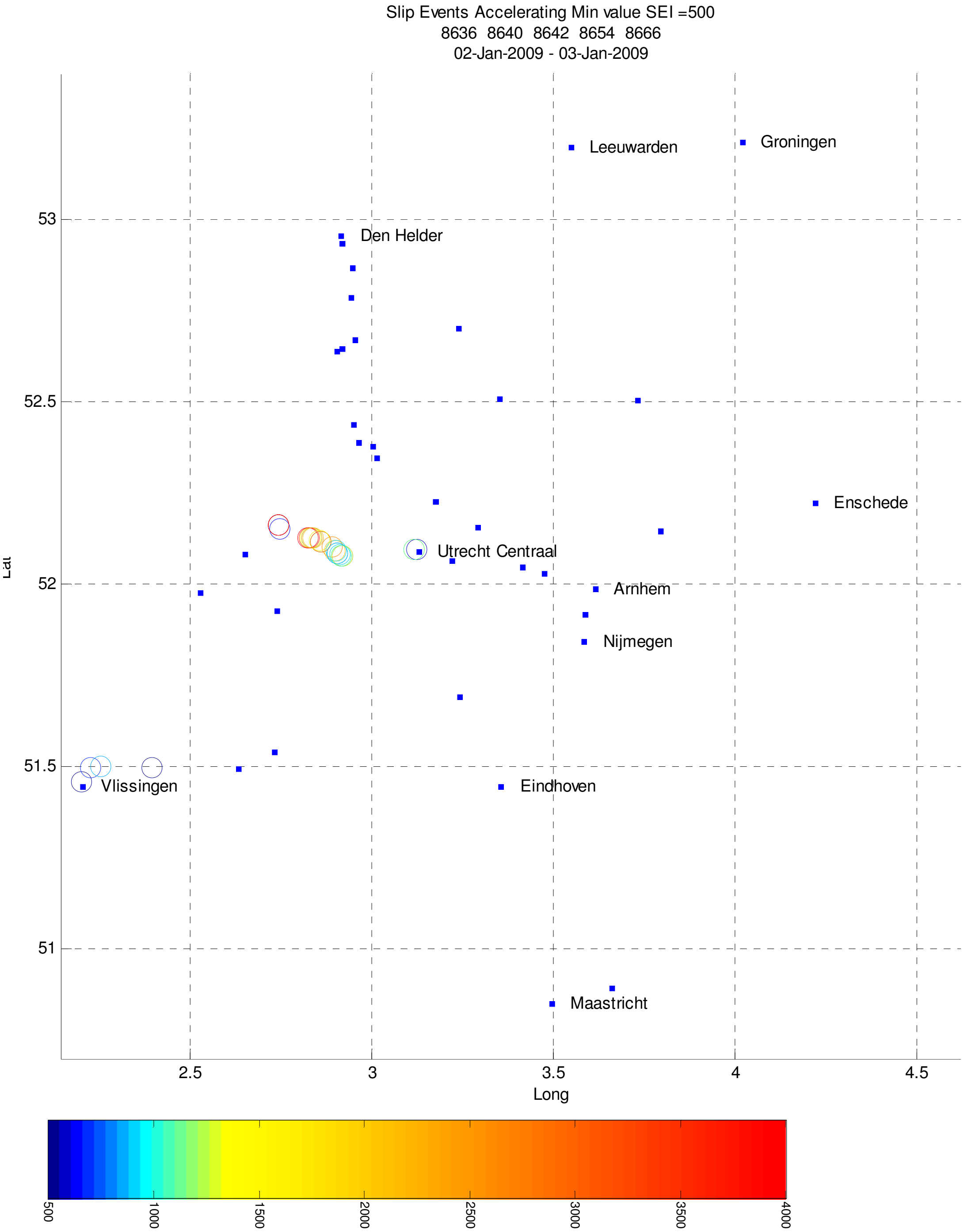


figure A6 Low adhesion in case of acceleration (traction); January 2, 2009.

Appendix B Time-distance diagrams

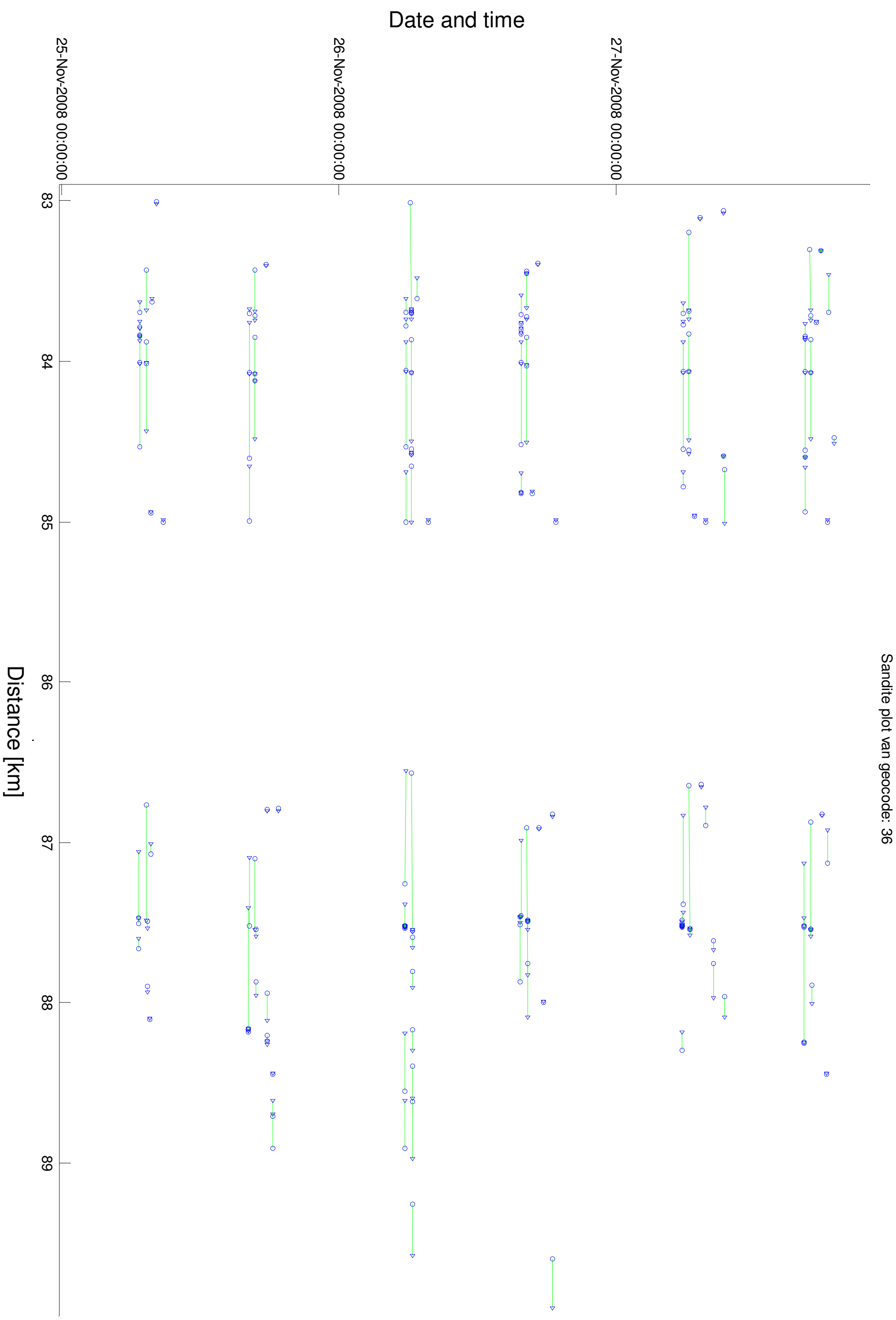


Figure B1

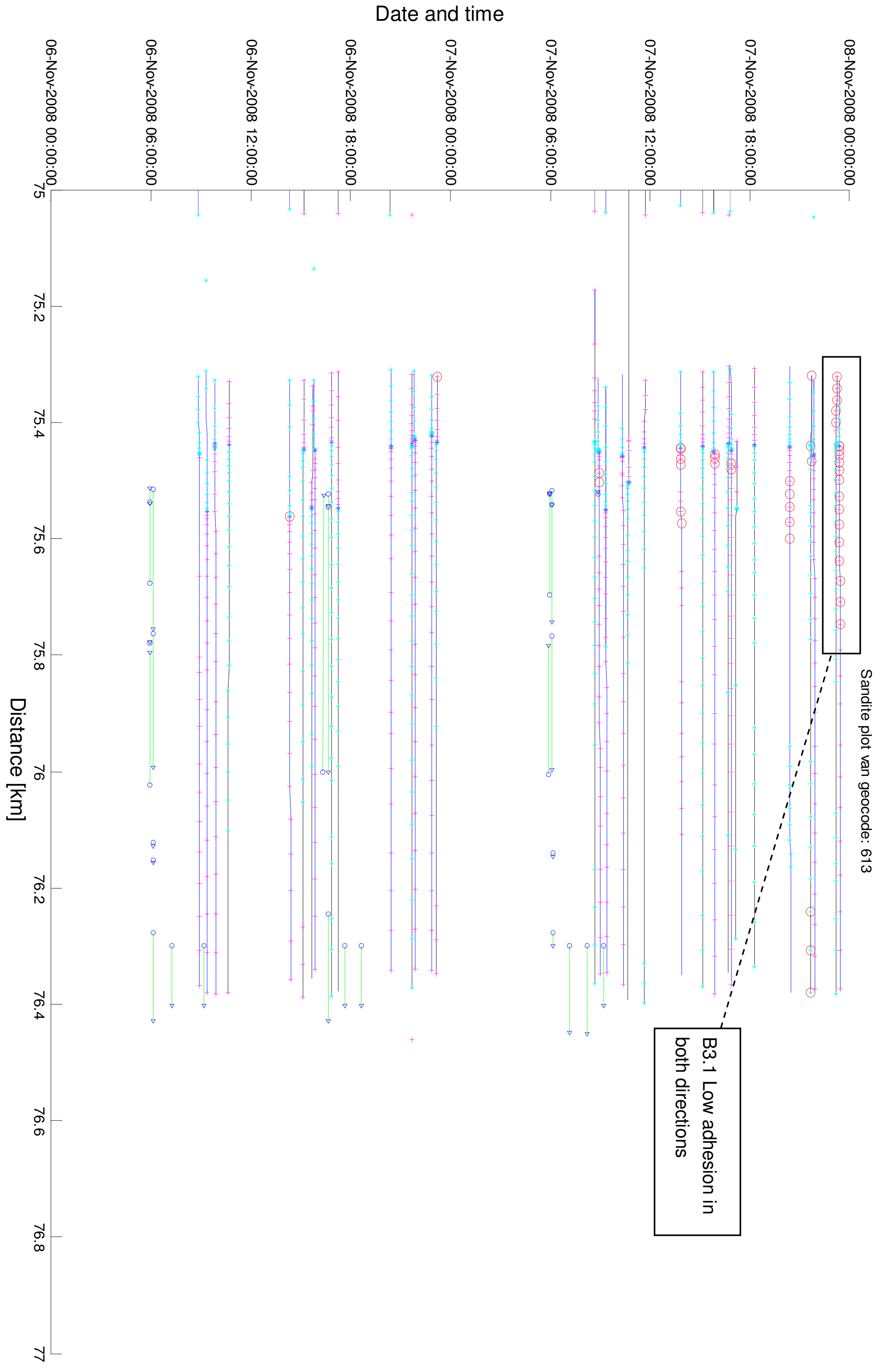
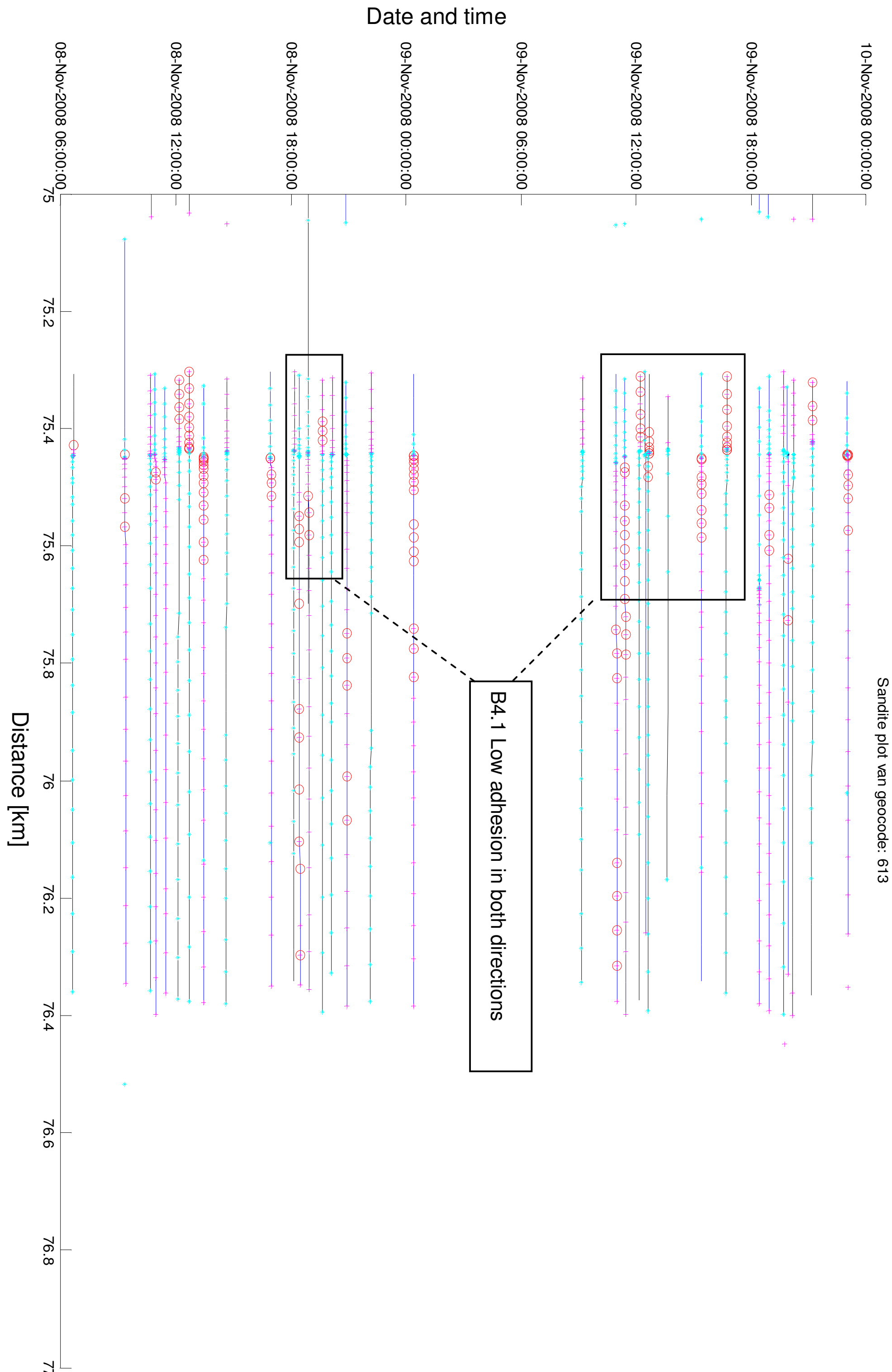
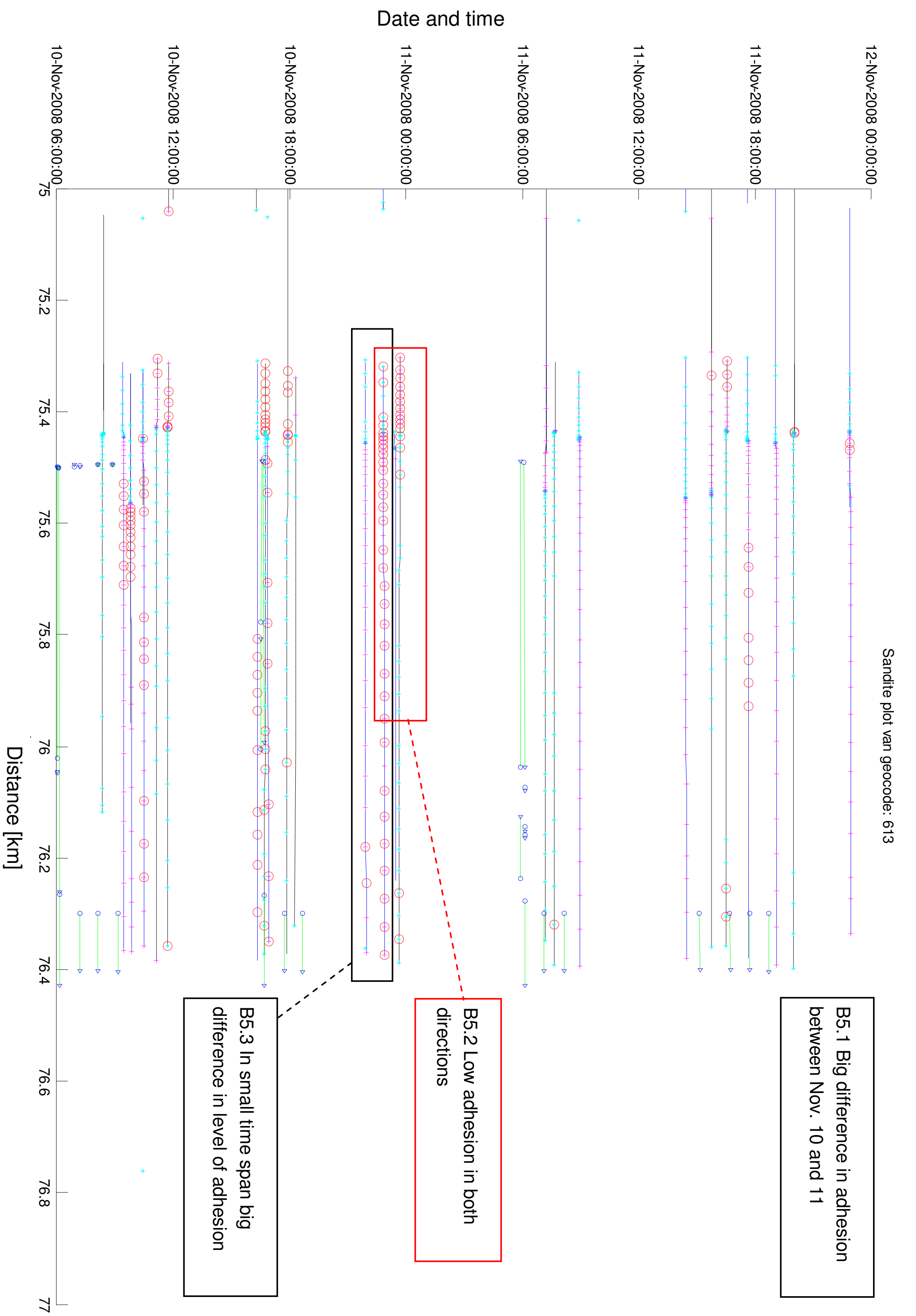


Figure B3 Time-distance diagram Ede-Wageningen November 6 and 7, 2008.



Figuur B4 Time-distance diagram Ede-Wageningen November 8 and 9, 2008.



Figur B5 Time-distance diagram Ede-Wageningen November 10 and 11, 2008.

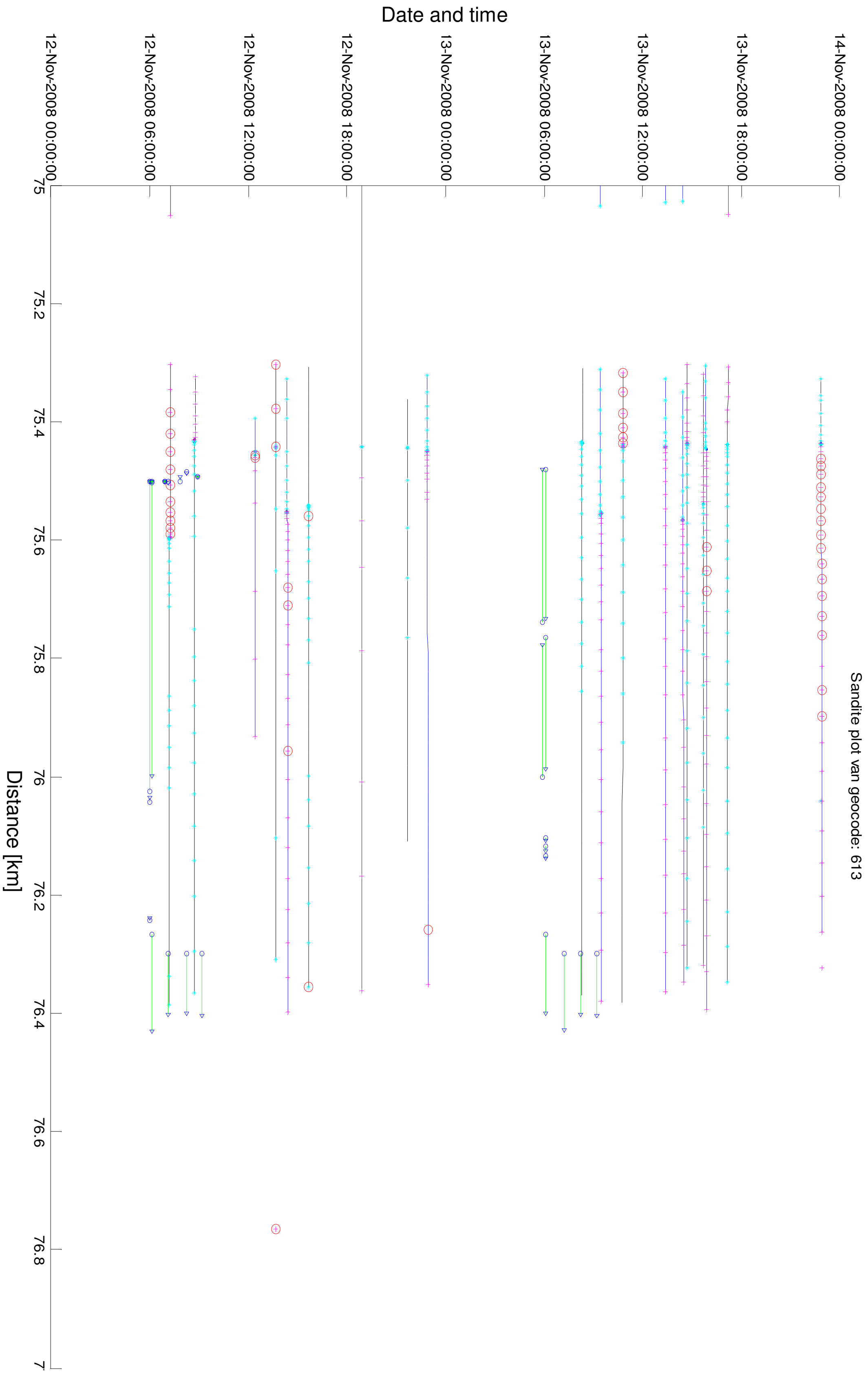


Figure B6 Time-distance diagram Ede-Wageningen November 12 and 13, 2008.

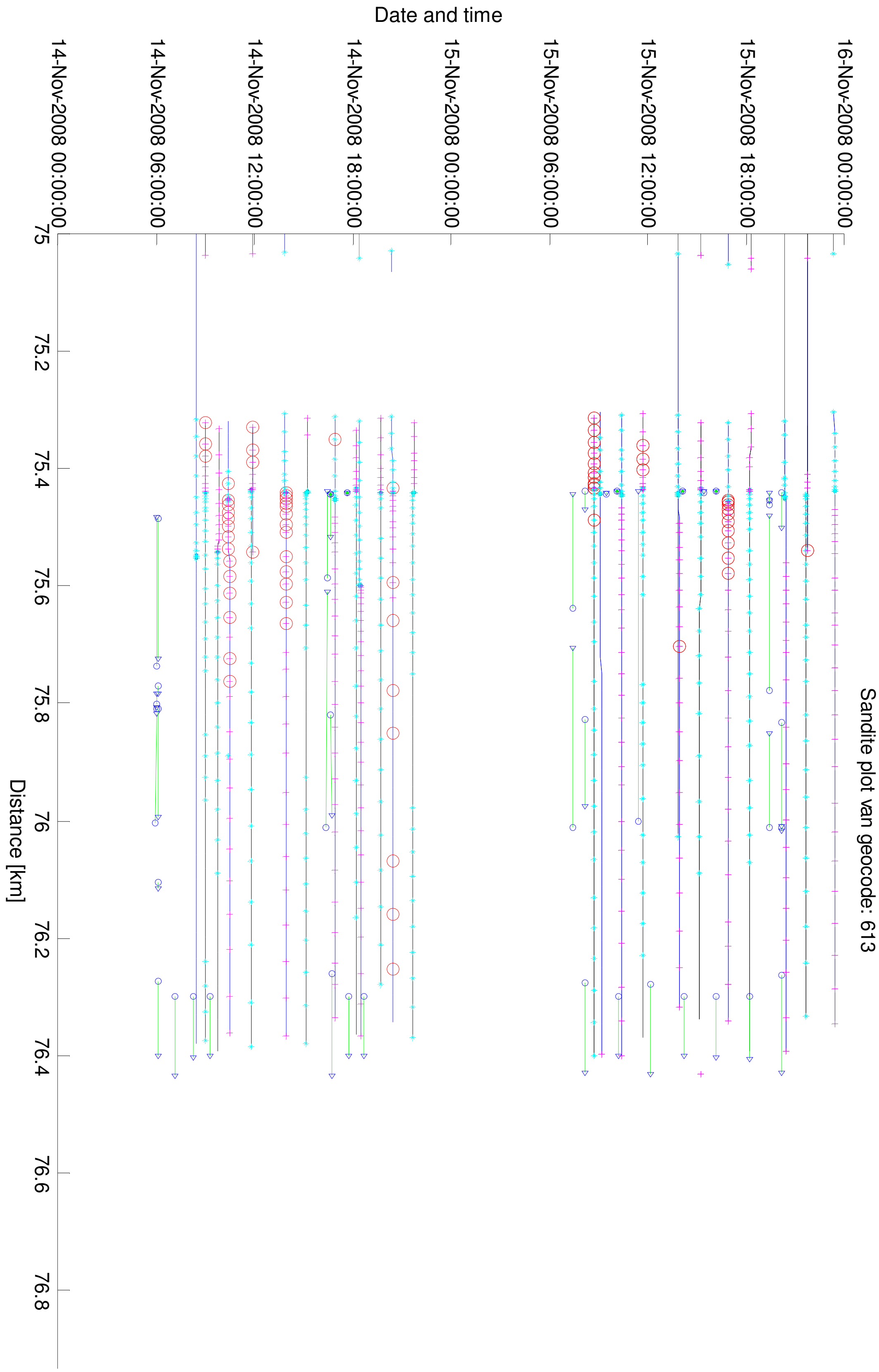


Figure B7 Time-distance diagram Ede-Wageningen November 14 and 15, 2008.

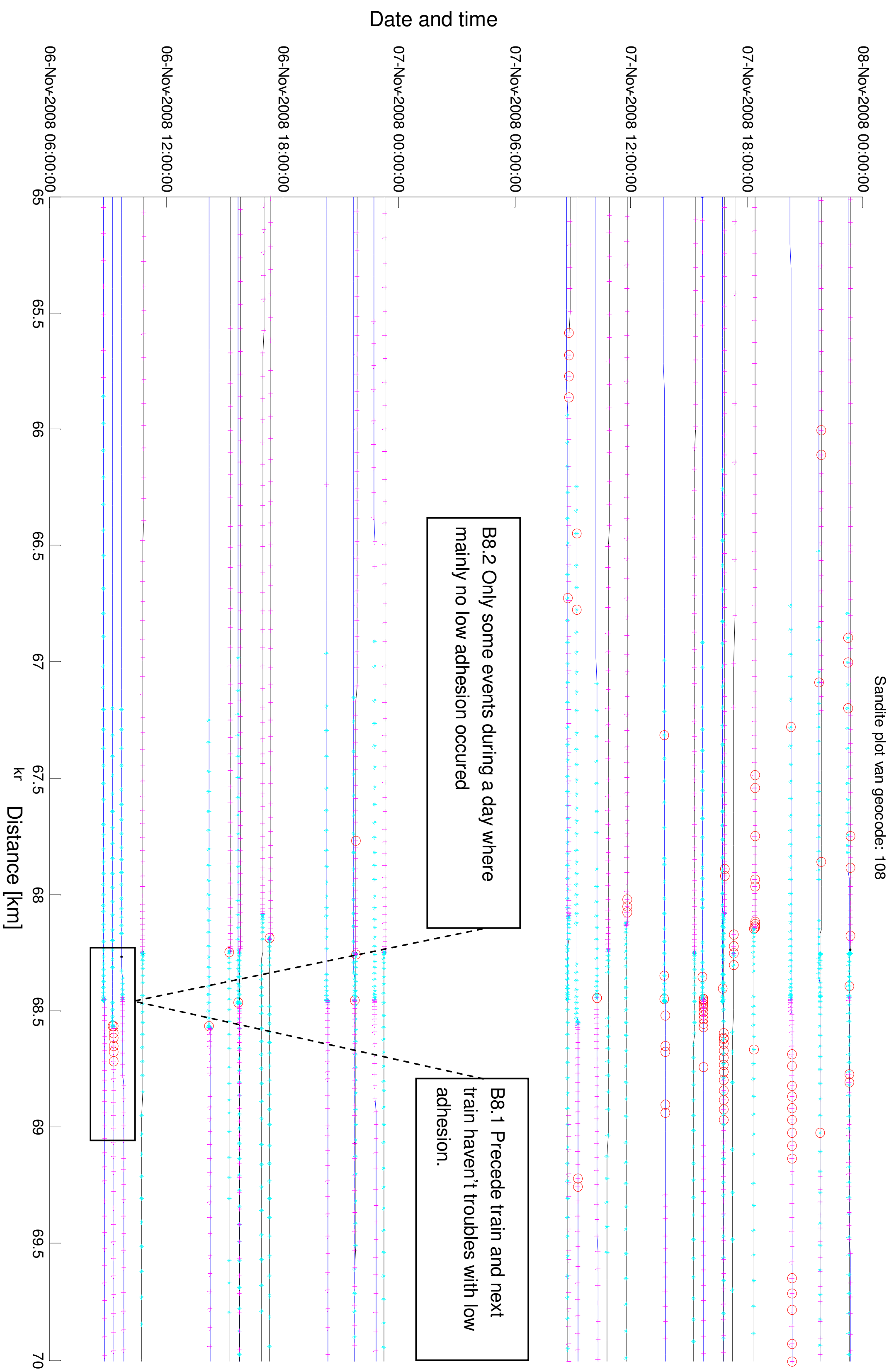
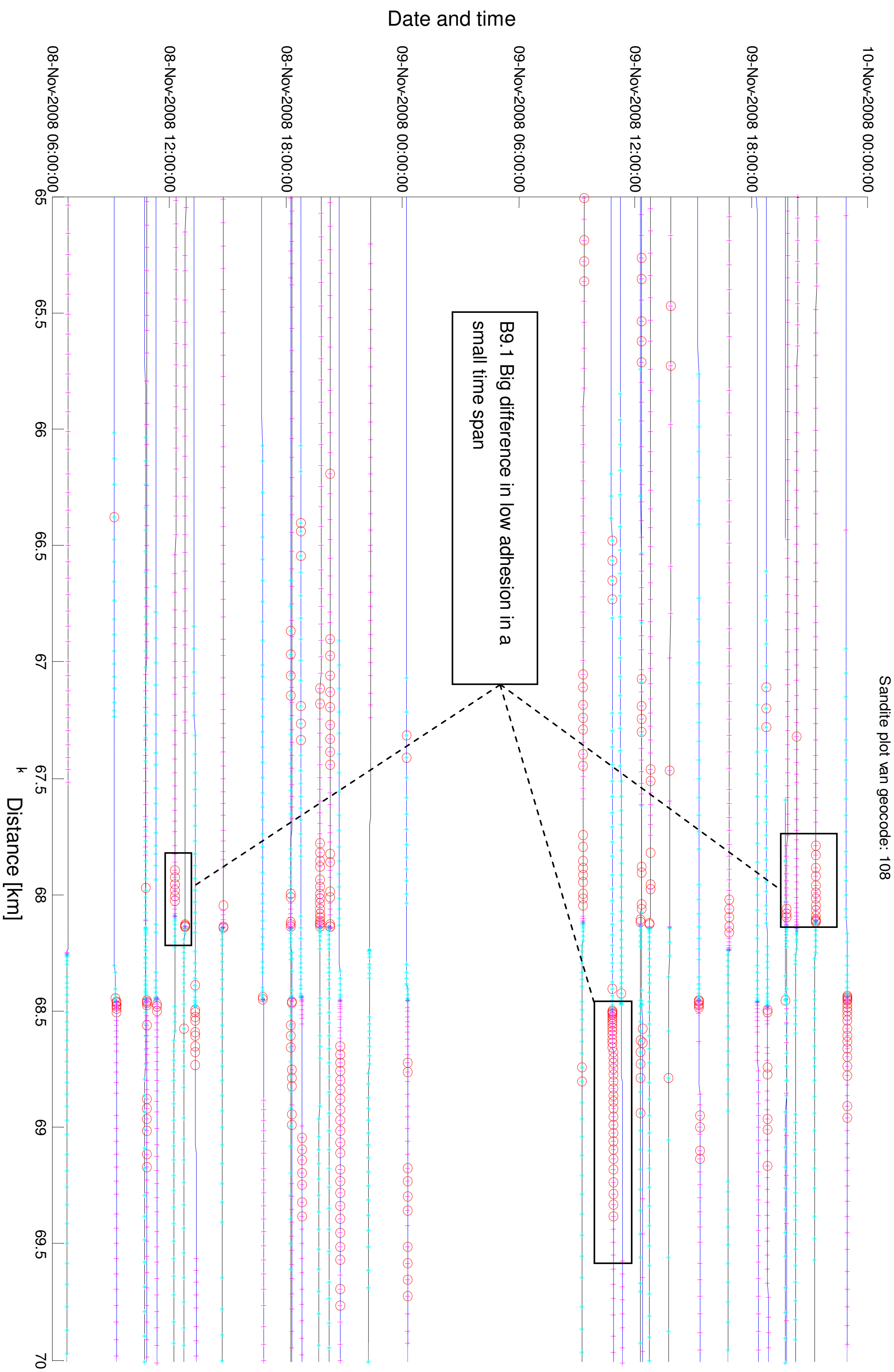
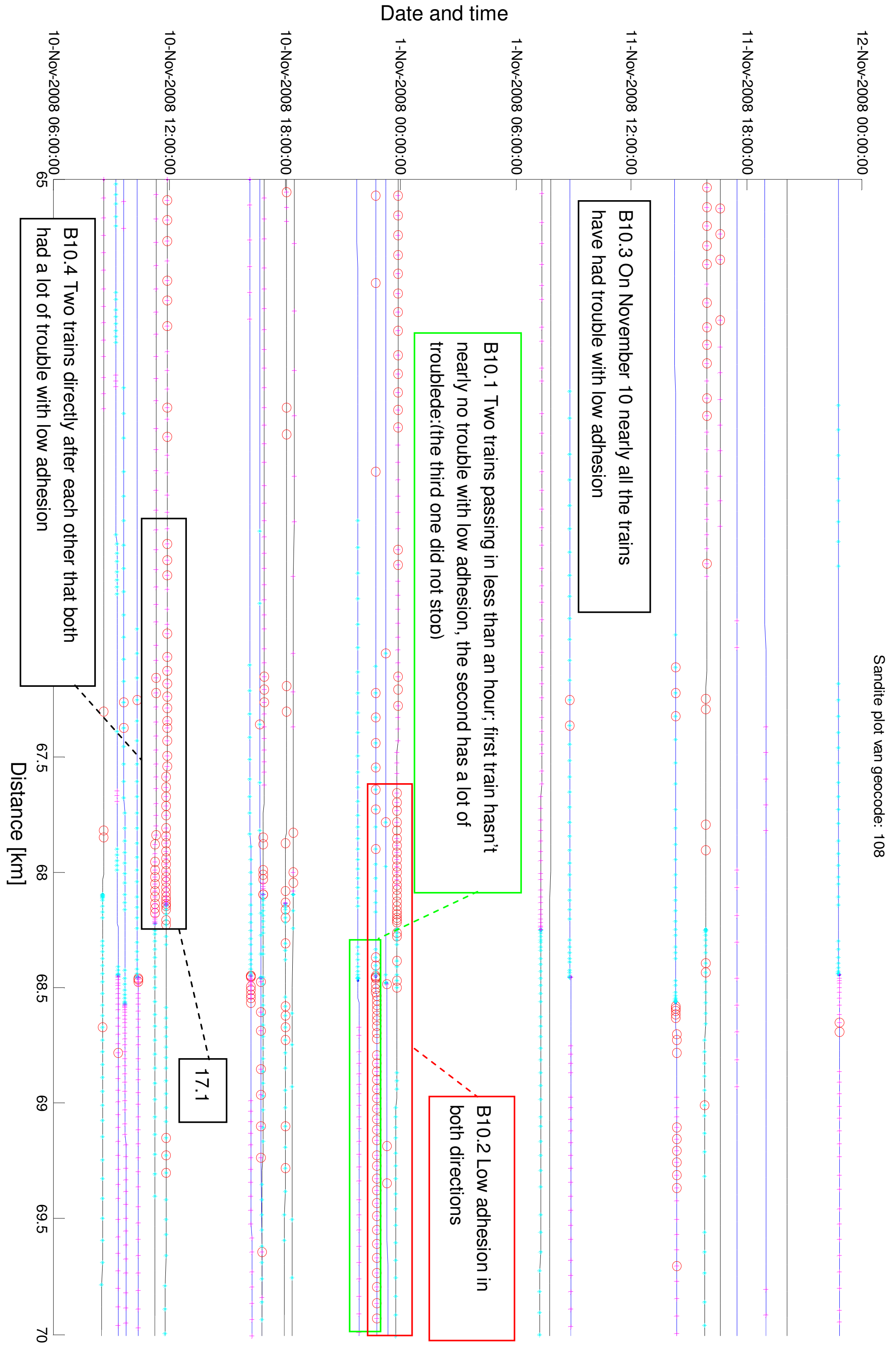


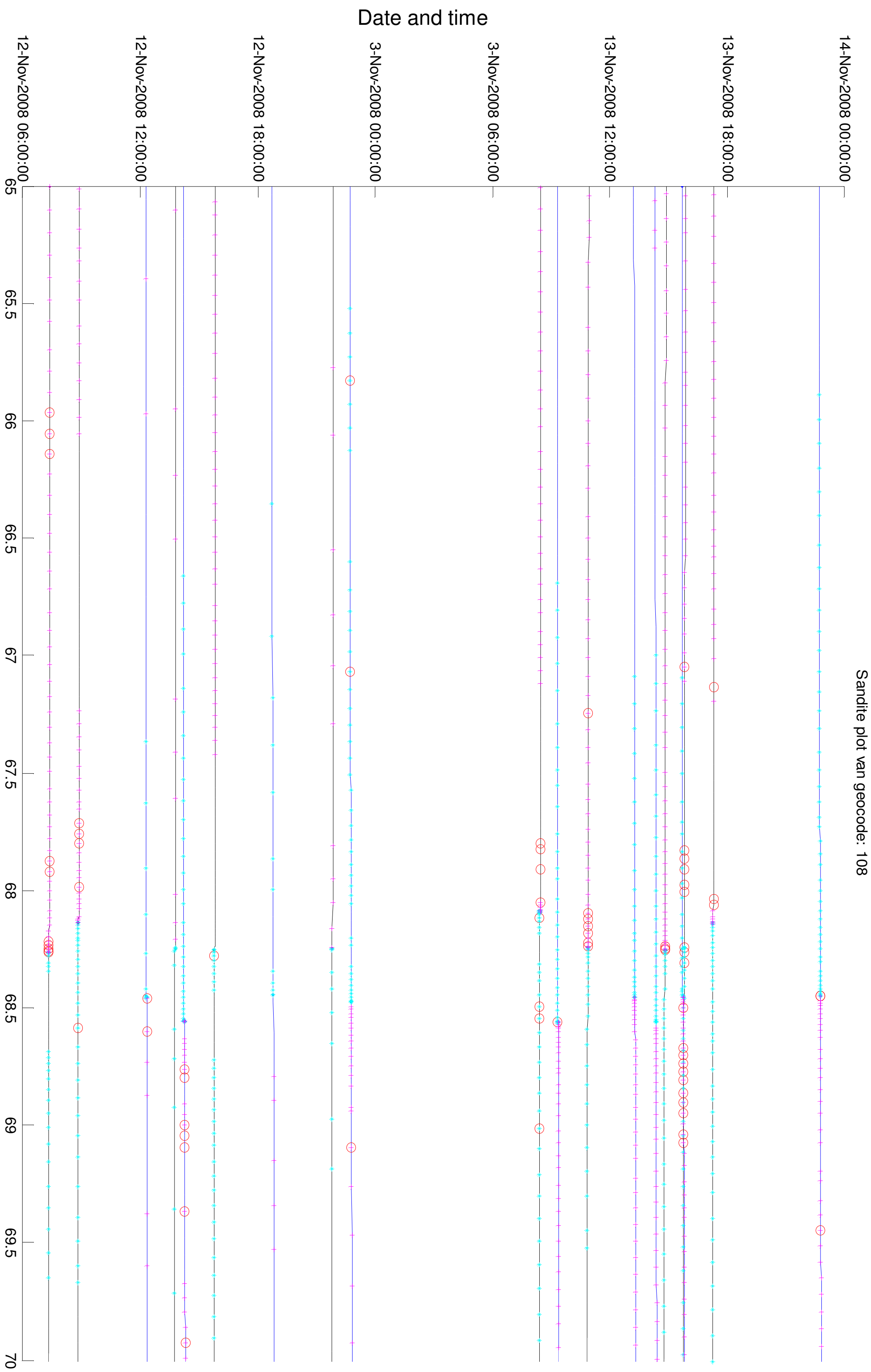
Figure B8 Time-distance diagram Veenendaal de Klomp November 6 and 7, 2008.



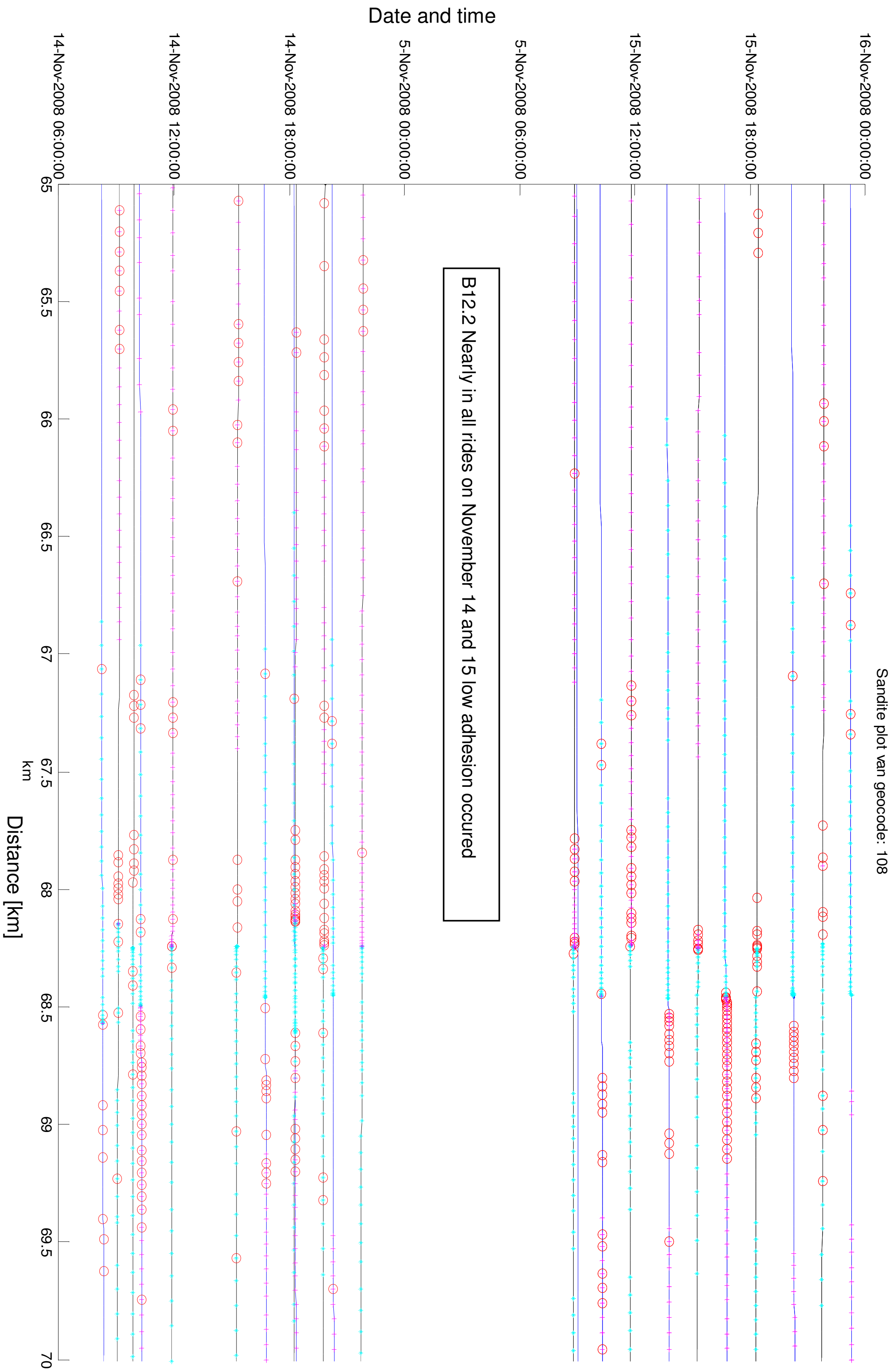
Figur B9 Time-distance diagram Veenendaal de Klomp November8 and 9, 2008.



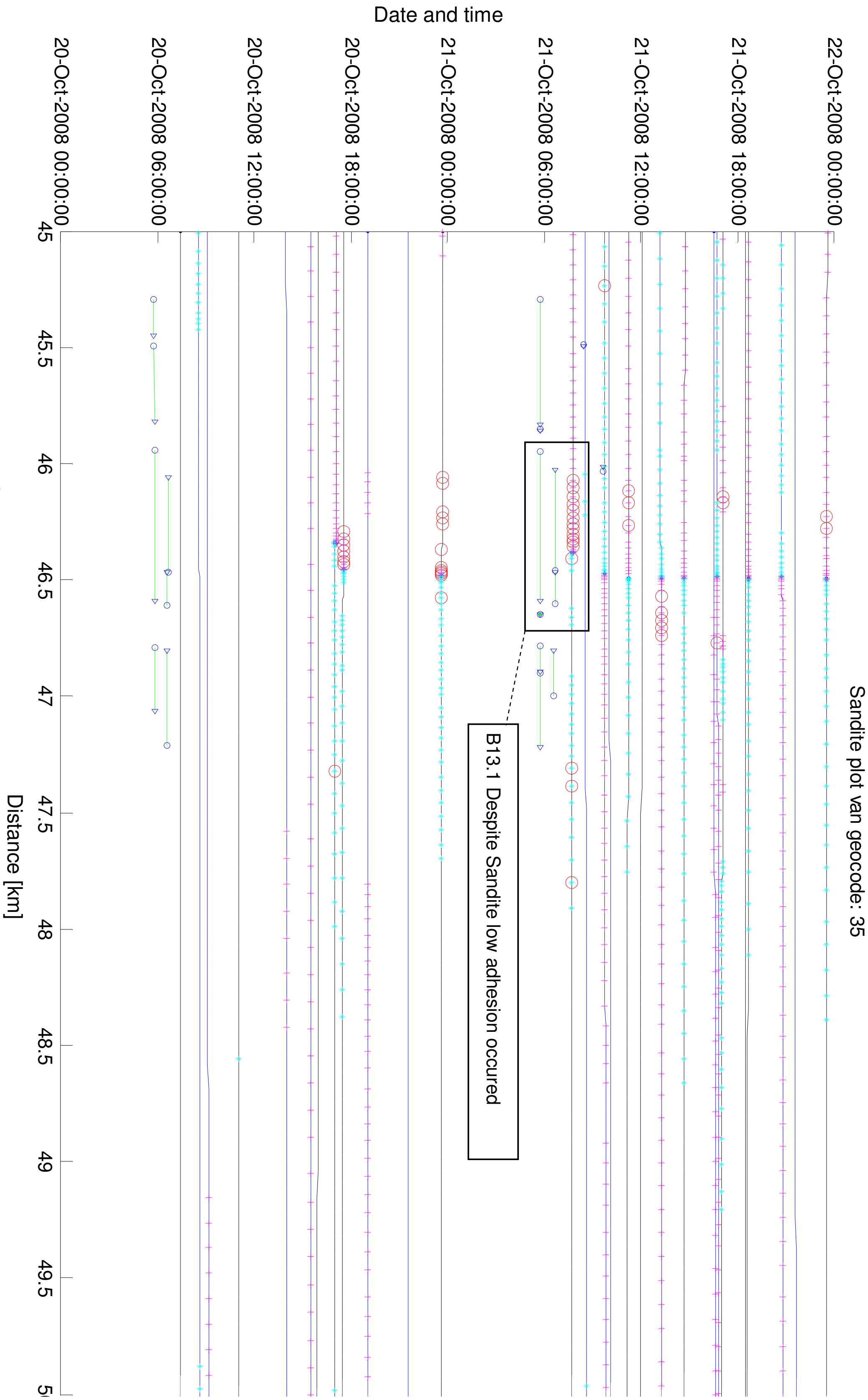
Figur B10 Time-distance diagram Veenendaal de Klomp November 10 and 11, 2008.



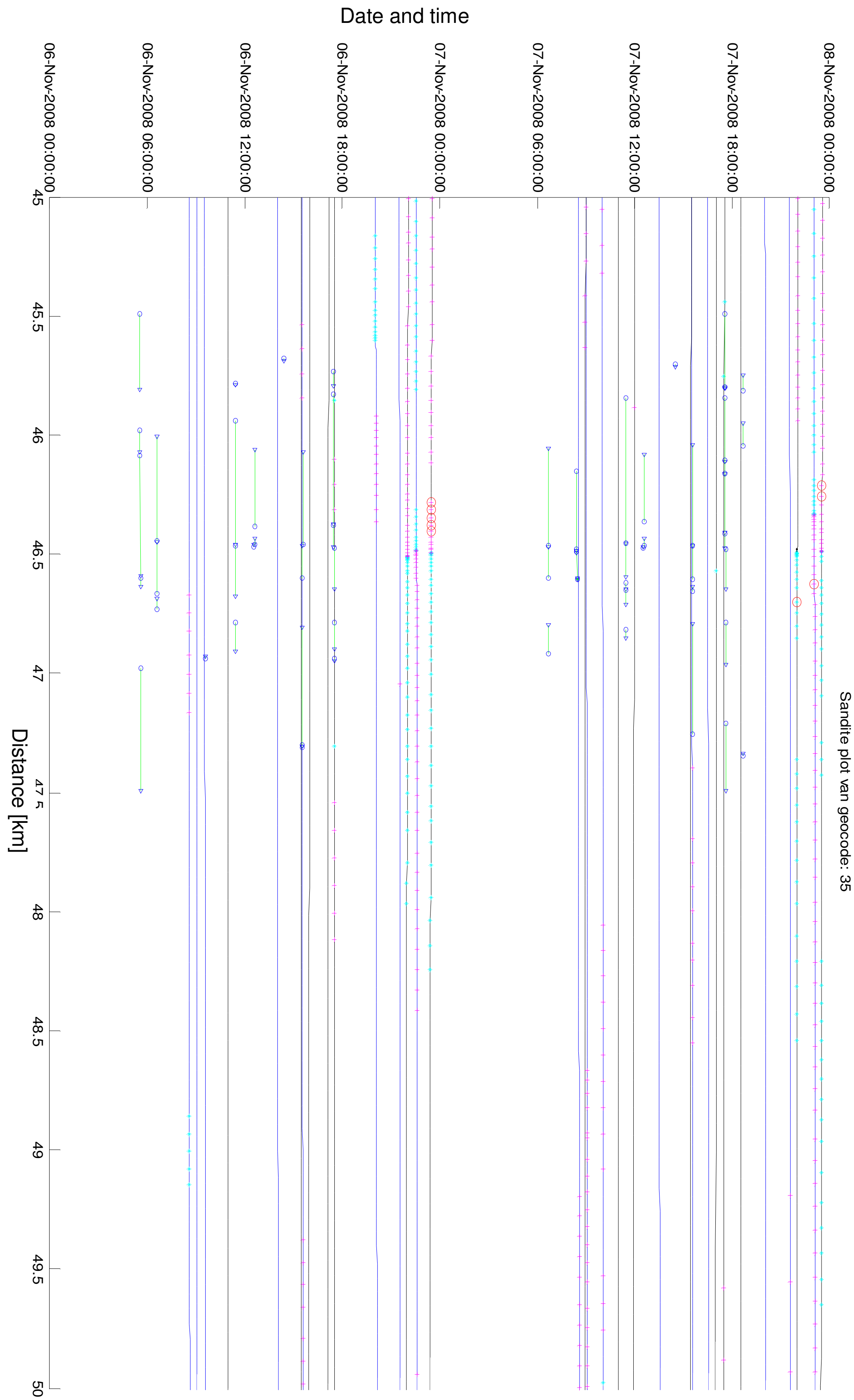
Figuur B11 Time-distance diagram Veenendaal de Klomp November 12 and 13, 2008.



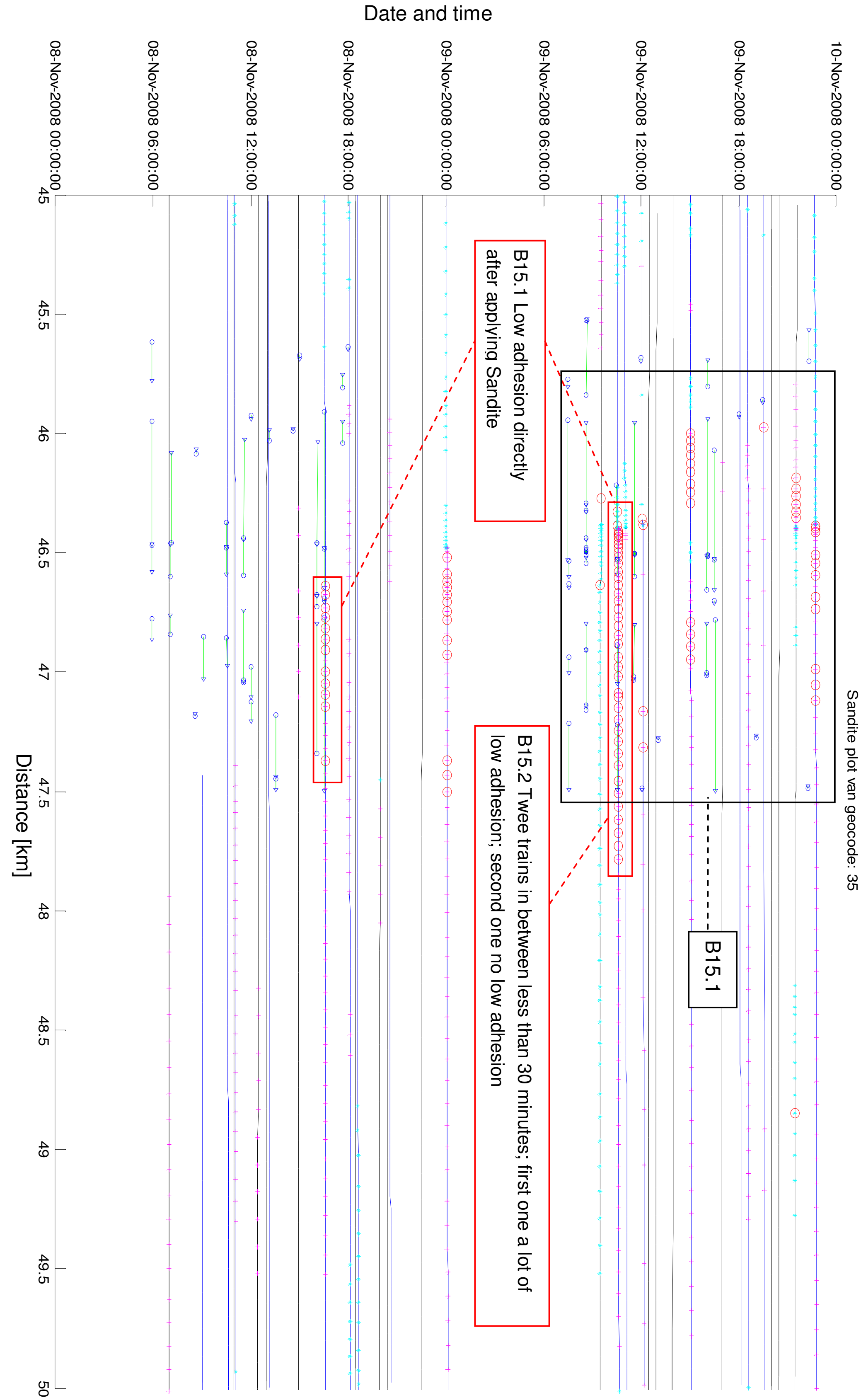
Figur B12 Time-distance diagram Veenendaal de Klomp November 14 and 15, 2008.



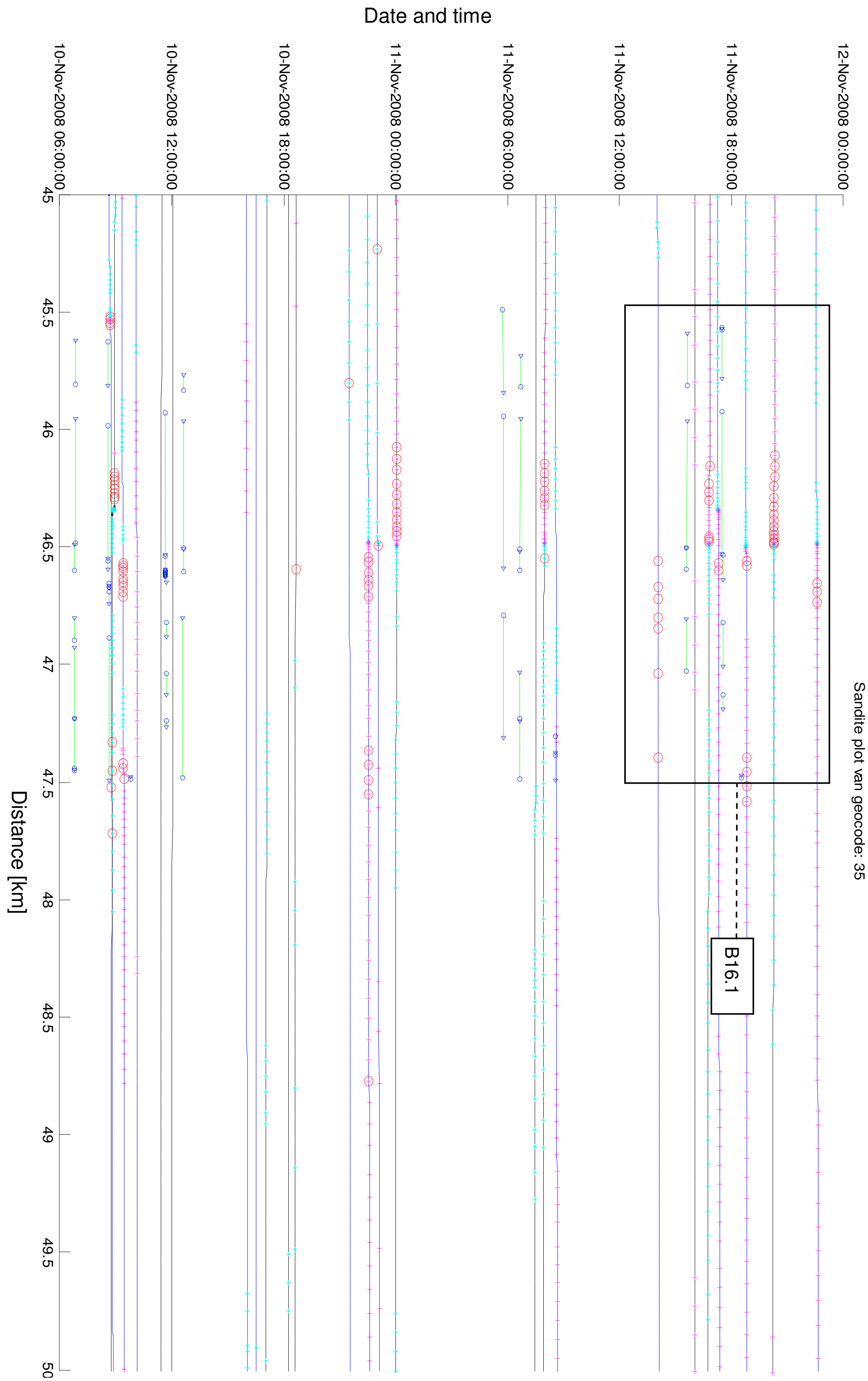
Figuur B13 Time-distance diagram Driebergen Zeist October 20 and 21, 2008.



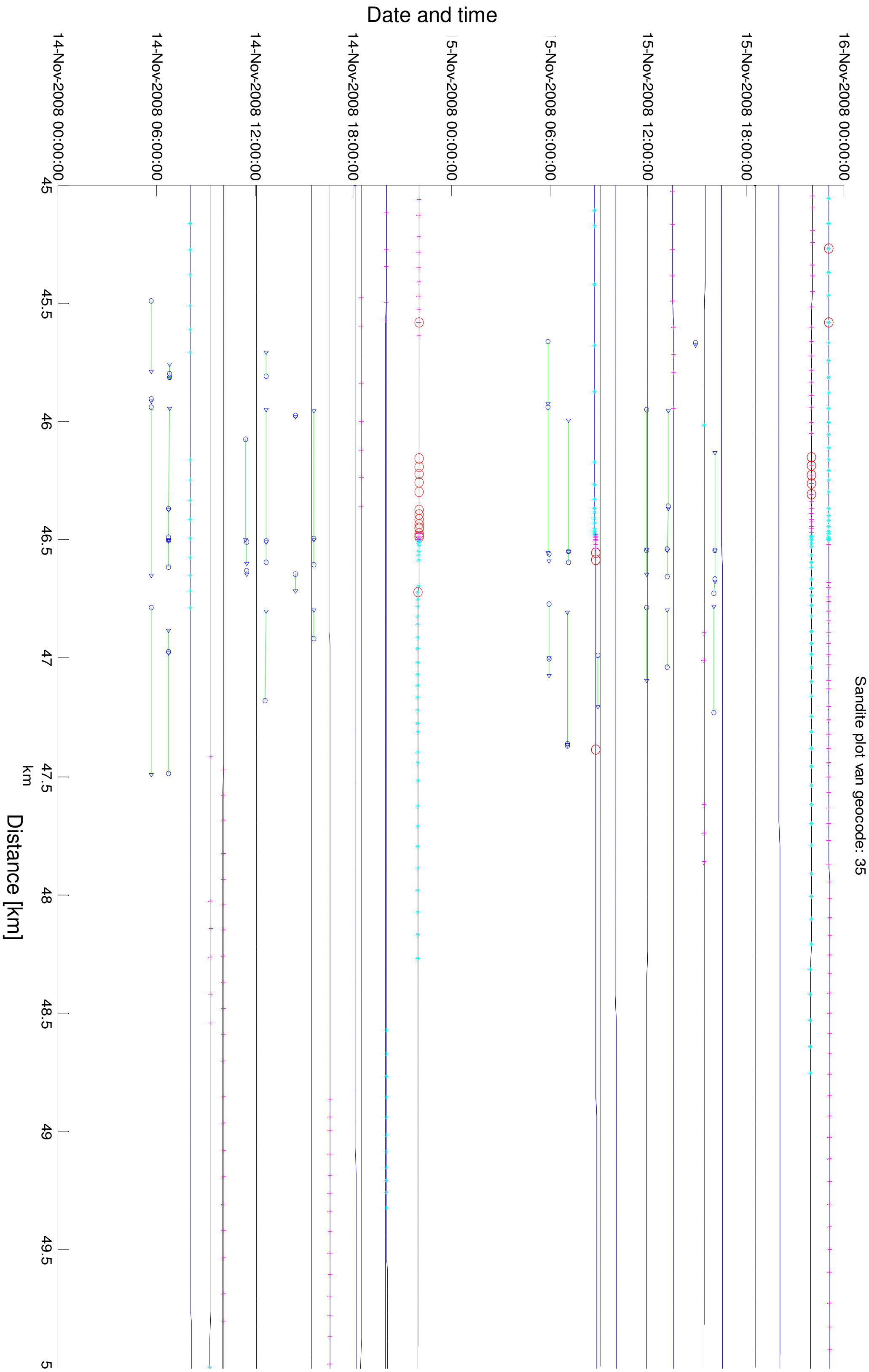
Figur B14 Time-distance diagram Driebergen Zeist November 6 and 7, 2008.



Figuur B15 Time-distance diagram Driebergen Zeist November 8 and 9, 2008.



Figur B16 Time-distance diagram Driebergen Zeist November 10 and 11, 2008.



Figur B17 Time-distance diagram Driebergen Zeist November 14 and 15, 2008.

Appendix C Speed-distance and time-distance diagrams

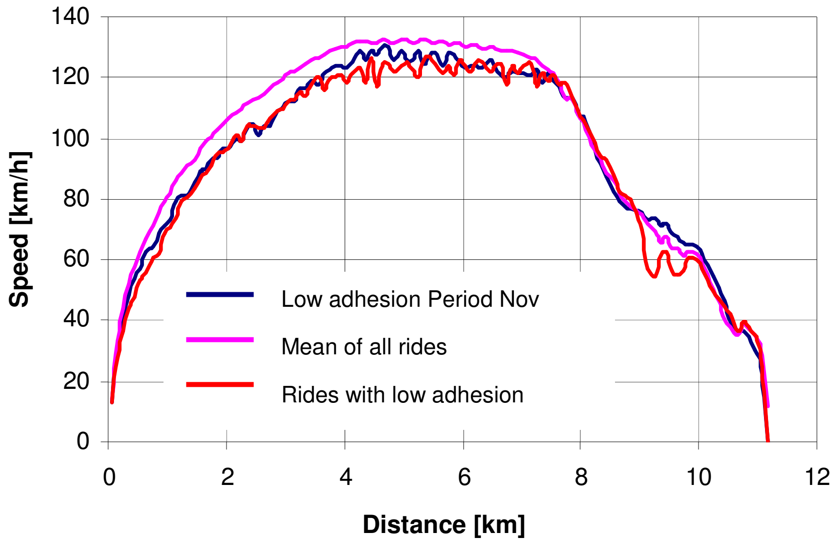


Figure C1 Speed-distance diagram of Driebergen-Zeist to Utrecht Centraal.

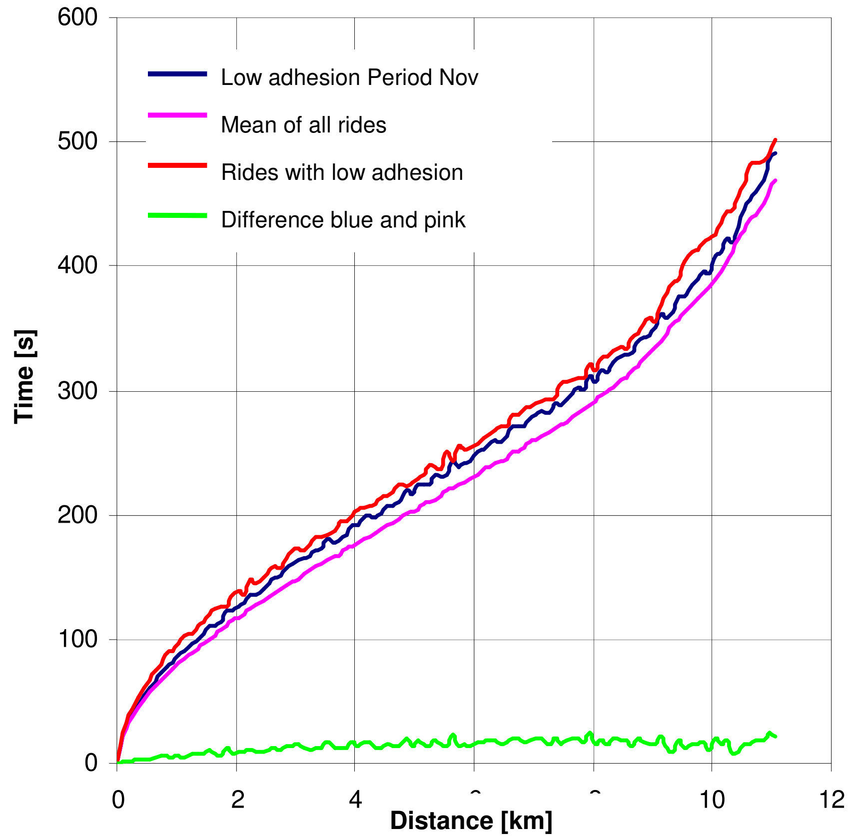


Figure C2 Time-distance diagram of Driebergen-Zeist to Utrecht Centraal.

531-35

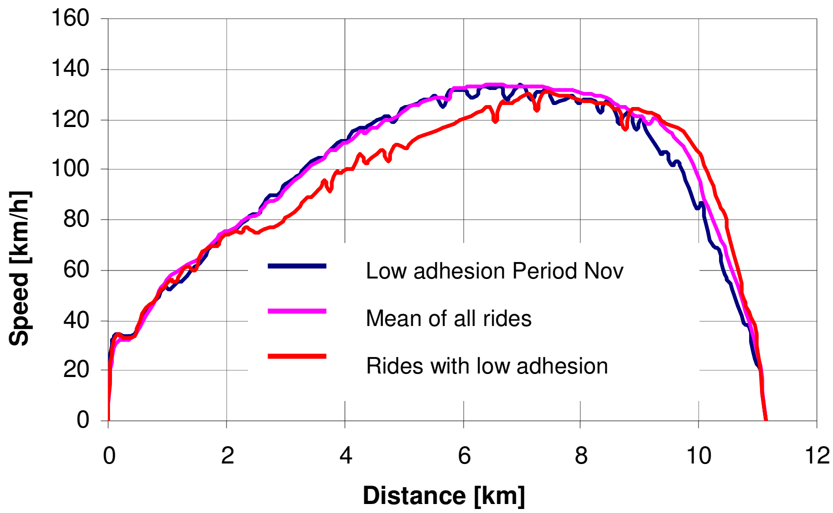


Figure C3 Speed-distance diagram of Utrecht Centraal to Driebergen-Zeist.

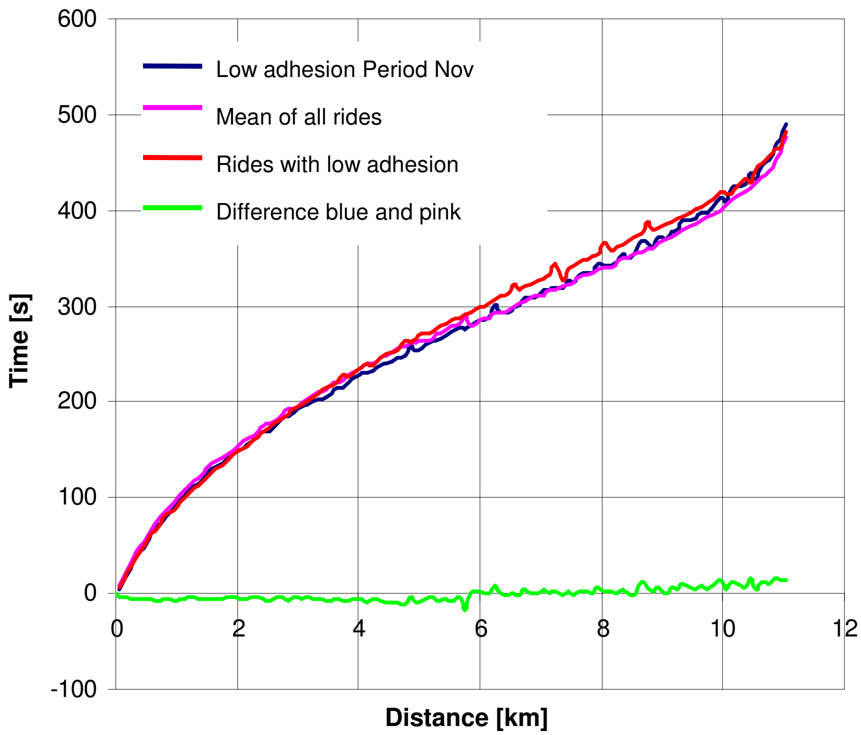


Figure C4 Time-distance diagram of Utrecht Centraal to Driebergen-Zeist.

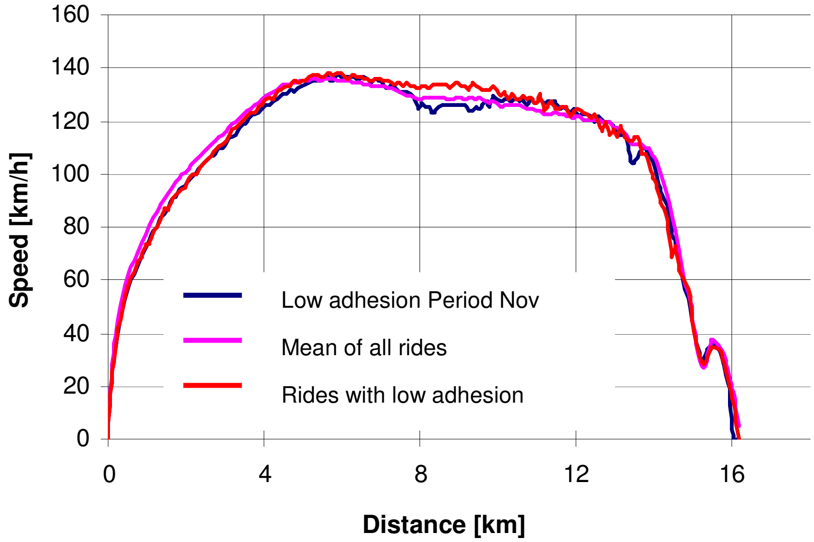


Figure C5 Speed-distance diagram of Ede-Wageningen to Arnhem.

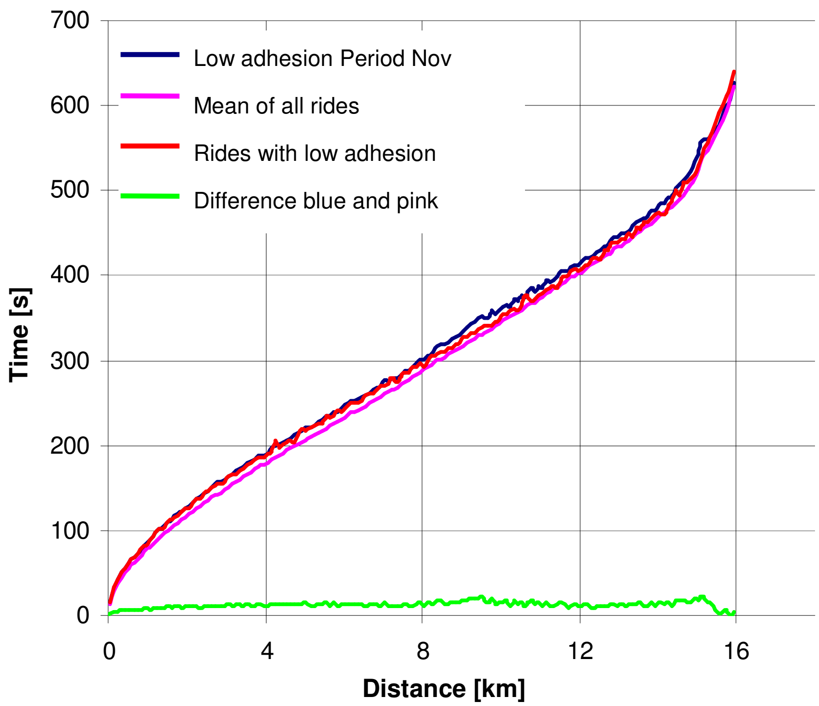


Figure C6 Time-distance-diagram of Ede-Wageningen to Arnhem.

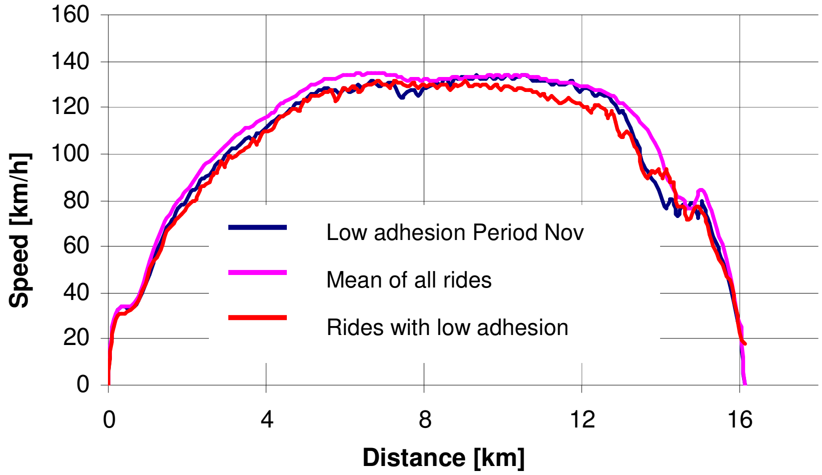


Figure C7 Speed-distance diagram of Arnhem to Ede-Wageningen.

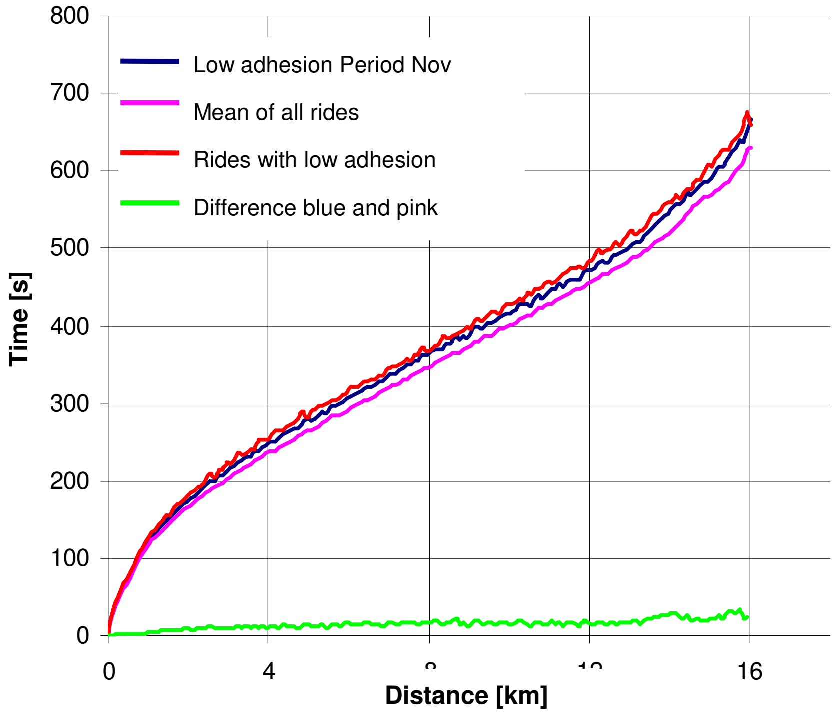


Figure C8 Time-distance diagram of Arnhem to Ede-Wageningen.

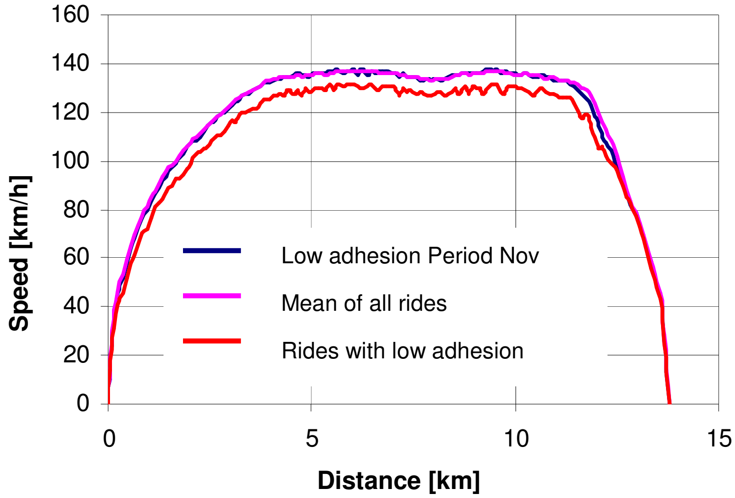


Figure C9 **Speed-distance diagram of Schagen to Heerhugowaard.**

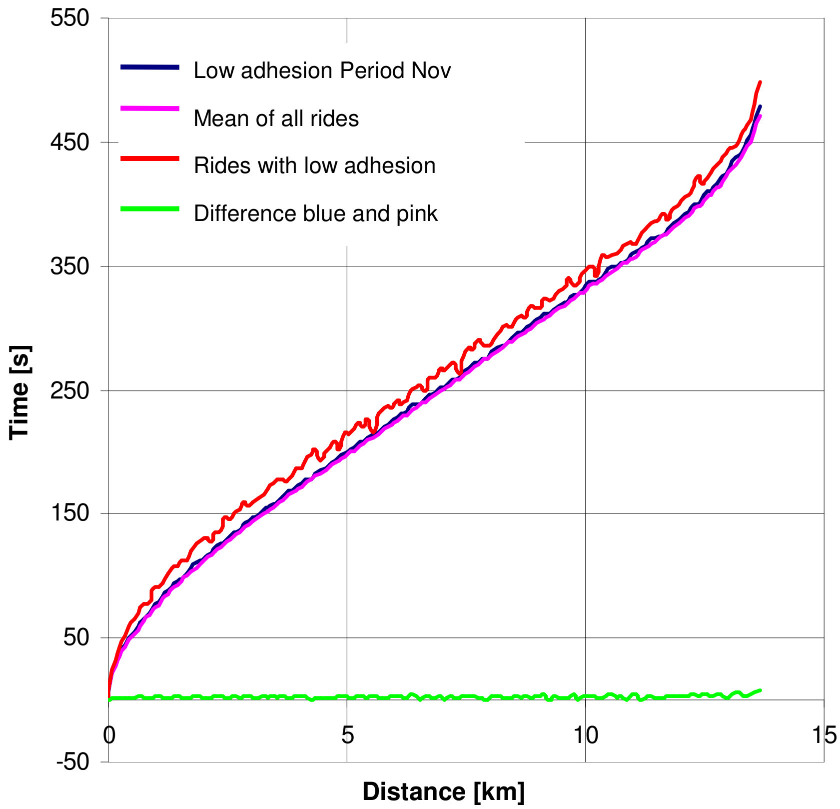


Figure C10 **Time-distance diagram of Schagen to Heerhugowaard.**

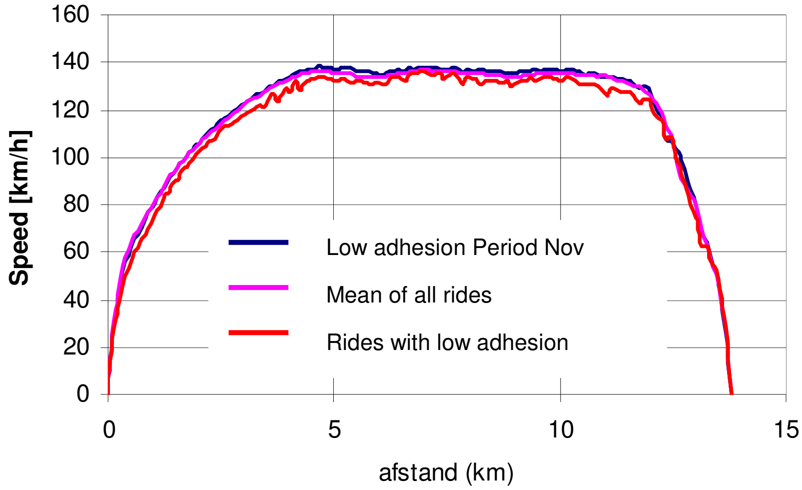


Figure C11 Speed-distance-diagram of Heerhugowaard to Schagen.

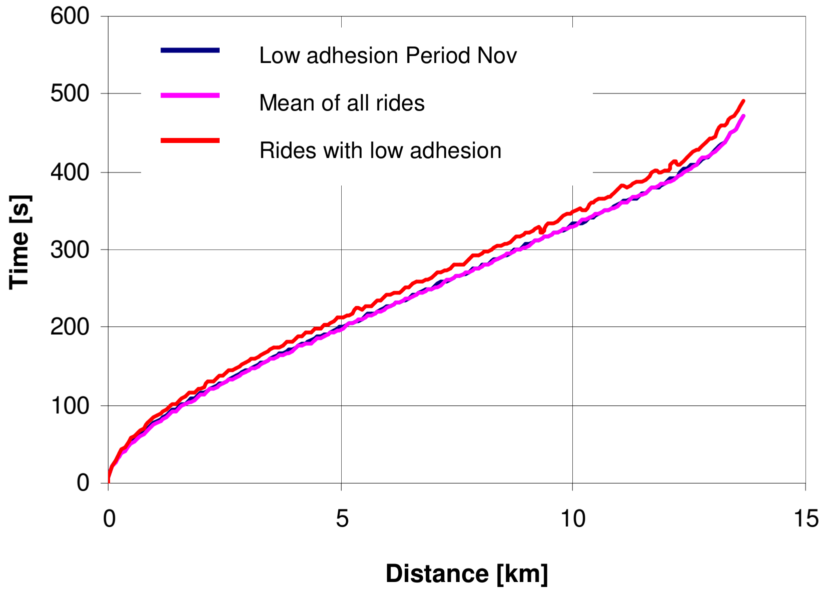


Figure C12 Time-distance diagram of Heerhugowaard to Schagen.

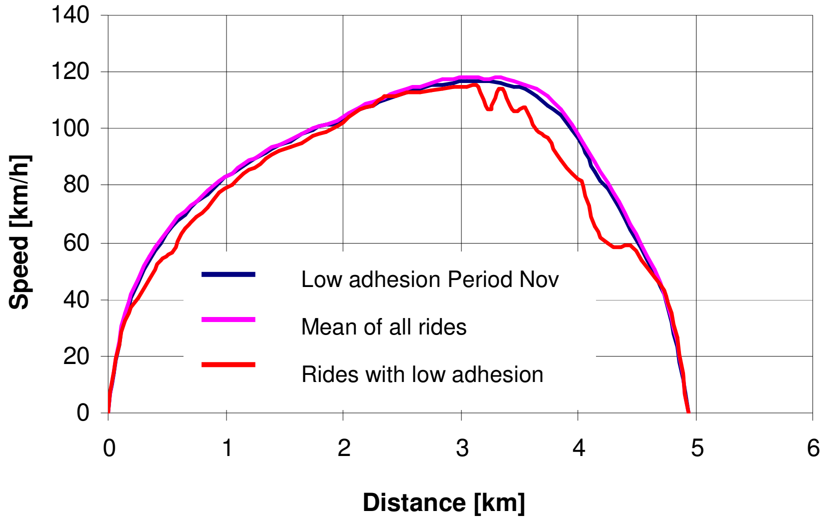


Figure C13 Speed-distance-diagram of Heerhugowaard to Alkmaar Noord.

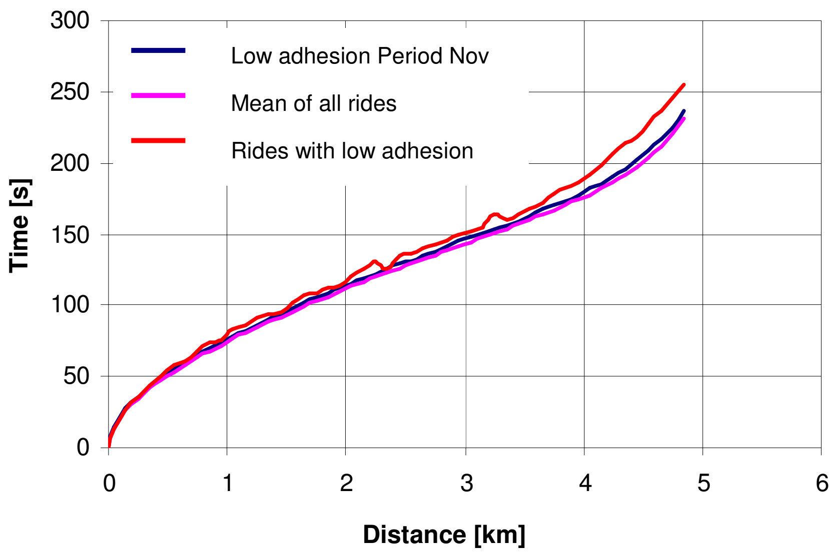


Figure C14 Time-distance-diagram of Heerhugowaard to Alkmaar Noord.

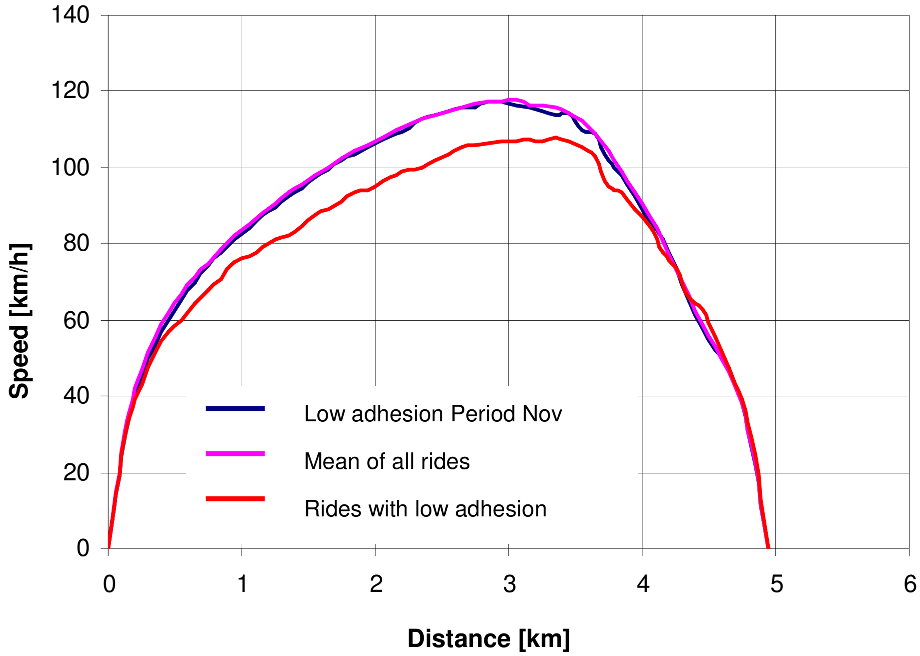


Figure C15 Speed-distance-diagram of Alkmaar Noord to Heerhugowaard.

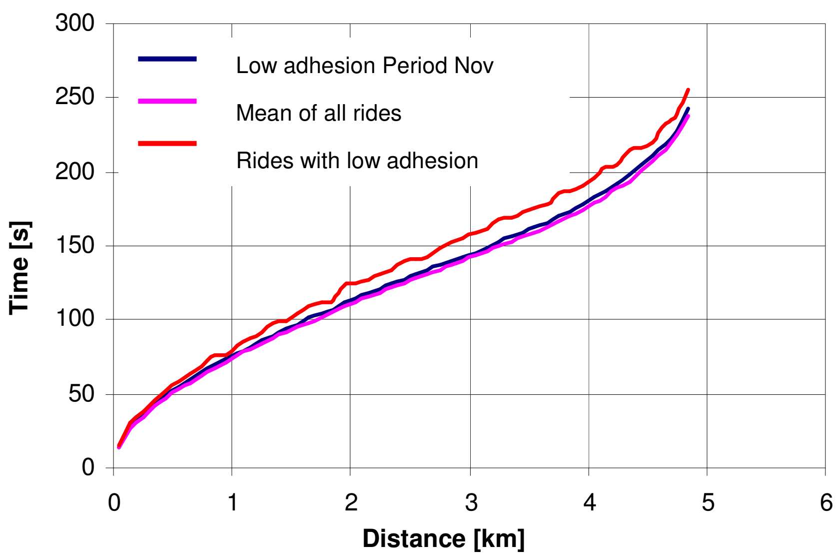


Figure C16 Time-distance diagram of Alkmaar Noord to Heerhugowaard.

Appendix D Speed-distance and Speed-time diagrams per ride

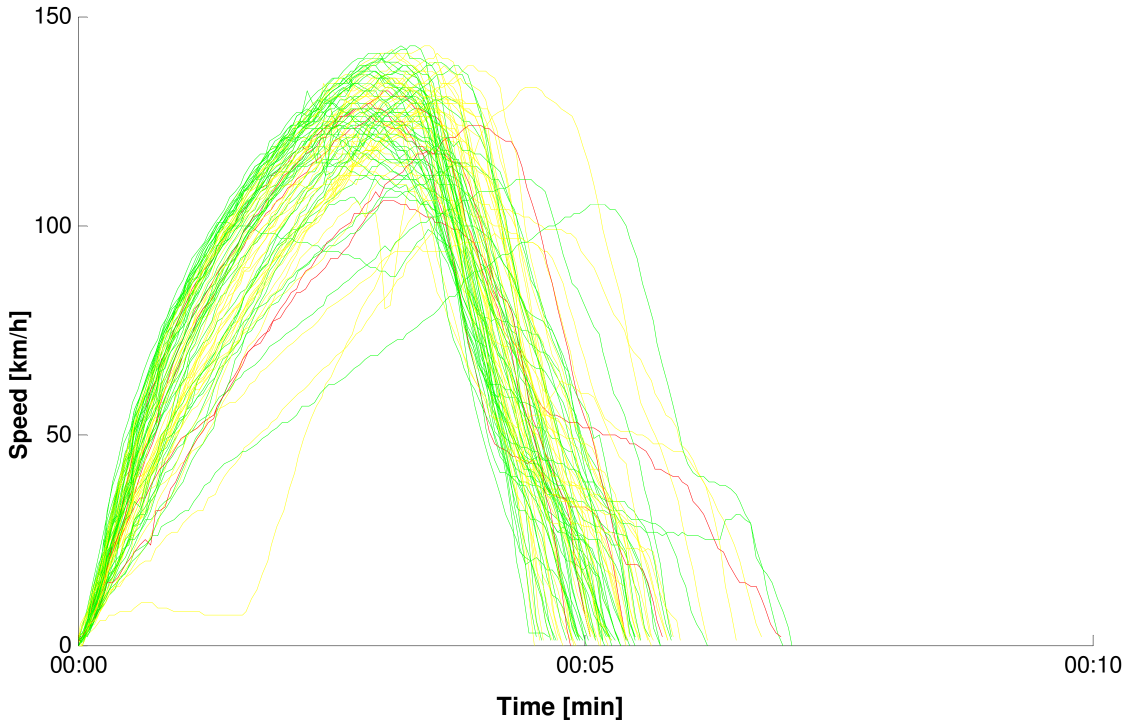


Figure D1 Speed-time diagram of Veenendaal-De Klomp to Ede-Wageningen (October 2008).

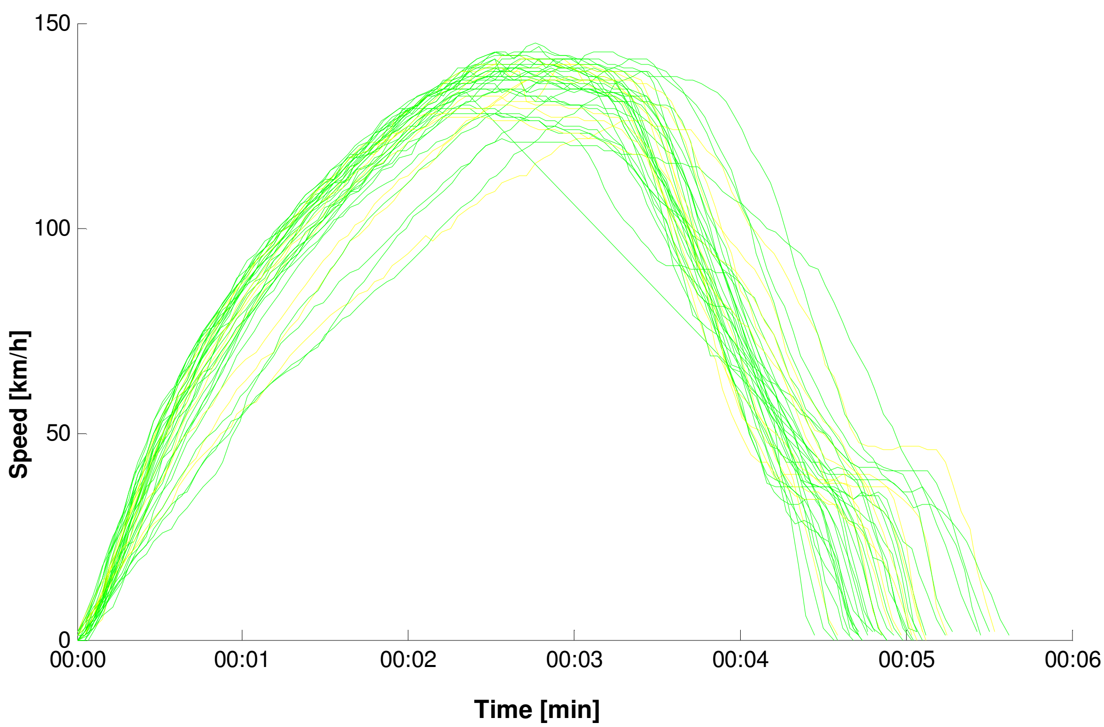


Figure D2 Speed time diagram of Ede-Wageningen to Veenendaal-De Klomp (Juli and August 2008).

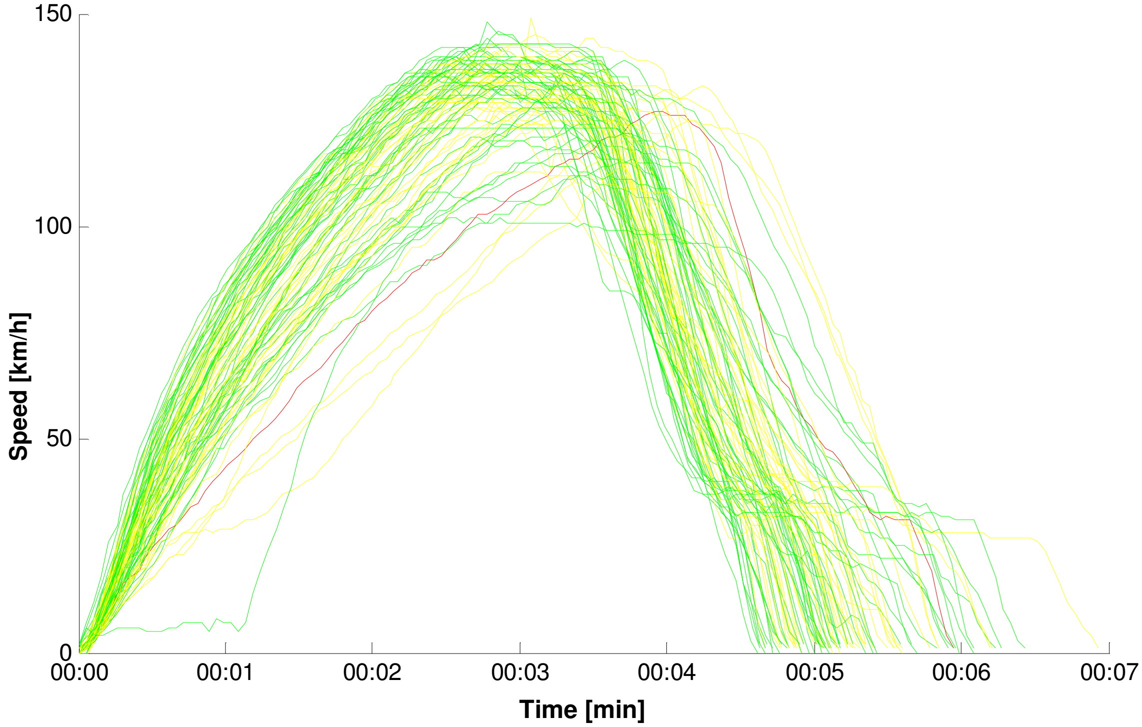
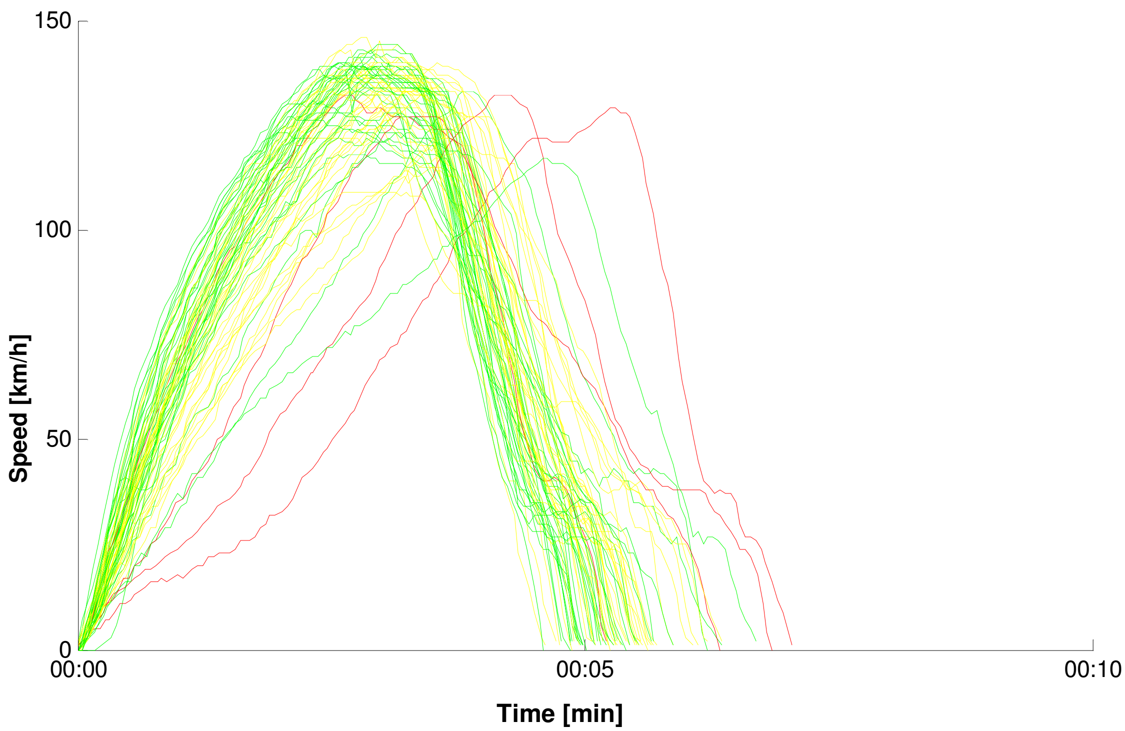


Figure D3 Speed-time diagram of Ede-Wageningen to Veenendaal De Klomp (October 2008).



Figuur D4 Speed-time diagram of Ede-Wageningen to Veenendaal-De Klomp (November 2008)

Appendix E Required traction level-distance diagrams

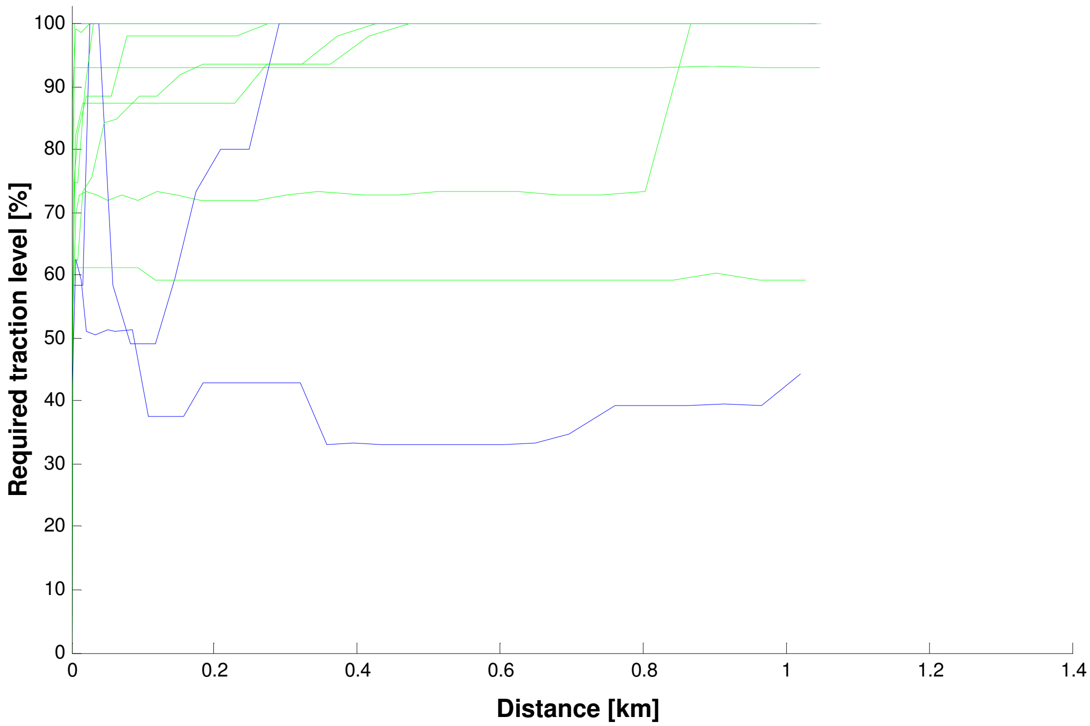


Figure E1 Required traction level-distance diagram of Veenendaal de Klomp to Ede Wageningen (October 1 through 8, 2008).

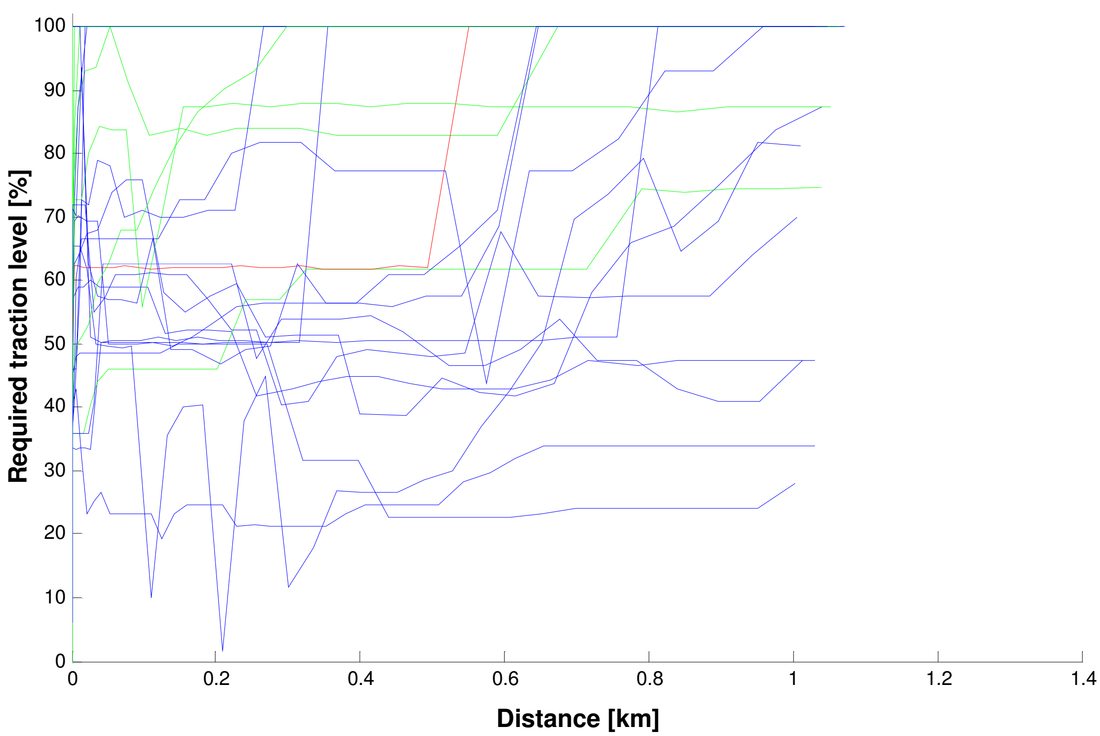


Figure E2 Required traction level-distance diagram of Veenendaal de Klomp to Ede Wageningen (October 9 through 16, 2008)

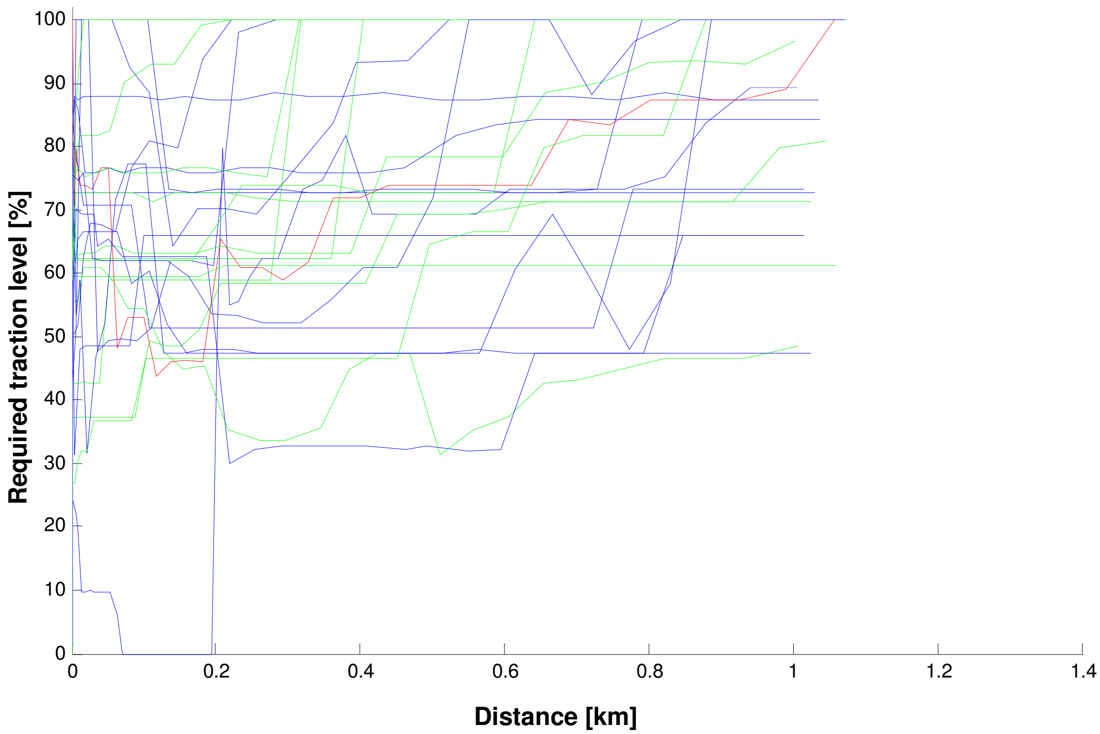


Figure E3 Required traction level-distance diagram of Veenendaal de Klomp to Ede Wageningen (October 17 through 24, 2008).

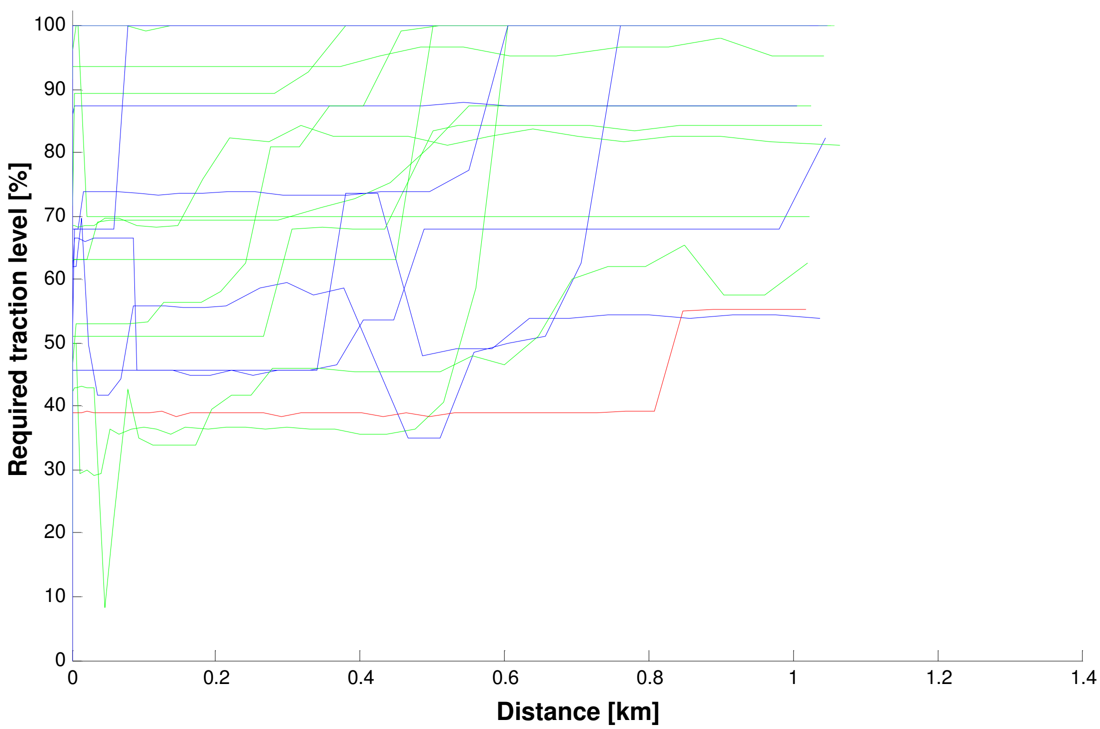


Figure E4 Required traction level-distance diagram of Veenendaal de Klomp to Ede Wageningen (October 24 through 31, 2008)

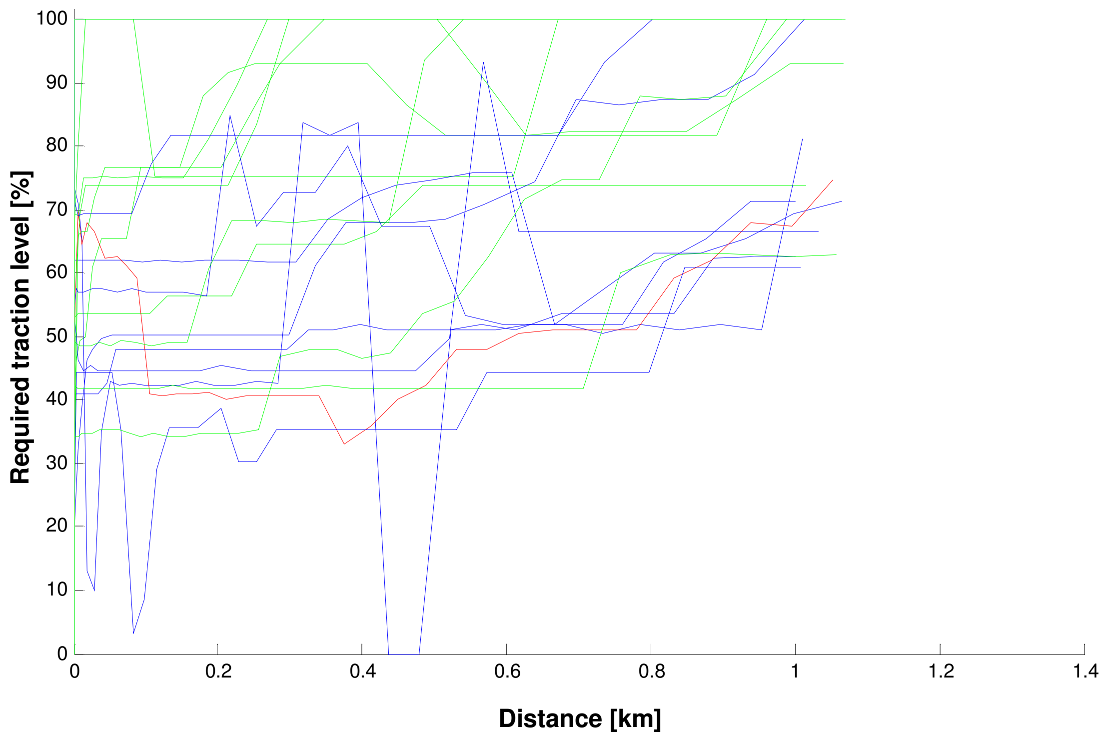


Figure E5 Required traction level-distance diagram of Veenendaal de Klomp to Ede Wageningen (November 1 through 8, 2008)

Appendix F Most severe clusters of events

Below a list is given with most severe clusters of events determined by the VIRM tribo trains:

1. VIRM tribo train with number 8642; on Sunday October 19 between 7.00 en 9.00 a.m. from station Arnhem to Nijmegen on both the way there and back.
2. VIRM tribo train 8654; on Sunday October 26 between 0.45 en 2.00 p.m. from station Veenendaal de Klomp via Arnhem to Nijmegen and again back to Arnhem.
3. VIRM tribo train 8636; on Wednesday November 5 between 00.30 and 2.30 uur p.m. from station Arnhem to Nijmegen on both the way there and back.
4. VIRM tribo train 8636; on Sunday November 9 around 10.00 p.m. from between station Utrecht Central and Arnhem.
5. VIRM tribo train 8640; on Monday November 10 around 12.00 between Driebergen-Zeist en Veenendaal de Klomp.
6. VIRM tribo train 8642; on Monday November 10 around 11.00 a.m. from station Arnhem to Veenendaal de Klomp.
7. VIRM tribo train 8654; on Monday November 10 around 10.00 a.m. from station Sittard to Heerlen on both the way there and back.
8. VIRM tribo train 8666; on Monday november 10 around 5.00 p.m from station Weert to Roermond and back again via Weert to Eindhoven
9. VIRM tribo train 8636; on Sunday November 16 between station Vlissingen and Roosendaal between 0.00 en 00.45 a.m and between 7.15 en 10.00 a.m and around 10.00 p.m.
10. VIRM tribo train 8636; on Monday November 17; between 5.00 en 6.00 a.m. from station Vlissingen to Roosendaal.
11. VIRM tribo train 8654 ; on Friday January 2 around 3.30 p.m. between station Bodegraven and Leiden.