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# Time Based Separation on Final Approach at Schiphol

Capacity study

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# 1 Introduction

Time based separation (TBS) on final approach is a concept to provide arrival capacity resilience to headwind. Traditionally, distance based separation (DBS) concepts are used on final approach. Flights are separated using distance based standards. In strong headwinds the aircraft ground speed is reduced and it takes longer to fly the required separation distance, hence the landing rate is reduced. By translating the required separation distance to a time based separation that takes into account the actual ground speed, the landing rate can be maintained without compromising safety.
The TBS concept has been developed within SESAR [1] and is one of the eight ATM system functionalities that have been identified for wide scale coordinated deployment as part of the Pilot Common Project. The European Commission has adopted a Regulation for the implementation of the Pilot Common Project [2].

NATS implemented TBS at Heathrow in spring 2015 [3]. In strong headwind conditions arrival capacity is recovered and delay due to strong headwind have reduced significantly. Benefits of TBS depend on fleet mix, speed profiles in approach and wind conditions.

Knowledge Development Centre Schiphol asked To70 to assess the effect of changing the separation rules on final approach at Schiphol from distance based separation to time based separation on arrival capacity. This study is the first step in building the business case to support the investment decision to put TBS on the ATM roadmap for Schiphol.

## 1.1 Study Objectives

The three main objectives of this study are:

- to give an insight in the characteristics of headwind conditions at Schiphol;
- to quantify the arrival capacity loss due to headwind;
- to quantify the capacity resilience of TBS

To meet the objectives, meteorological, runway usage and radar data have been analyzed and runway throughput simulations have been conducted for TBS and DBS concepts.

## 1.2 Main Findings

*Headwind conditions*

Analysis of the headwinds on final approach, showed there are significant differences between runways, seasons, and time of day. On average a headwind of 7 kts is encountered at ground level. Headwinds of more than 10kts and 20kts are encountered 20% and 3% of the time, respectively. Average values for individual runways vary between 4 kts and 18 kts. Traffic arriving on runways 27 and 22 is exposed to the highest headwind speeds. Strong headwind (>20 kts) are most frequent in winter and at the middle of the day.

*Capacity loss*

There is an almost linear relation between headwind and capacity loss. Every 5 kts of headwind, runway capacity is reduced by approximately 1 AC/h. For the Schiphol fleet mix, a 25 kts headwind results in a 15% loss of arrival capacity. On days with strong headwinds, arrival capacity is reduced by 60 to 80 aircraft per day compared to days with light headwinds. On average 8 days per year only one runway can be used for arriving traffic, due to wind conditions.

*Time Based Separation Concepts*

Two TBS concepts have been studied to assess the effect on runway capacity resilience to headwind. A TBS concept with system support, comparable to the Heathrow TBS concept and procedural TBS. The main difference is the level of system support to apply the TBS distances. The TBS distance between aircraft is calculated using the prevailing headwind on the glideslope and wake turbulence time based separation and aircraft ground speed. TBS is only applied on wake pairs (e.g., a medium aircraft following a heavy aircraft). For non-wake pairs DBS procedures are used.

In the TBS concept with system support, the TBS distance is displayed on the radar display. In the procedural TBS concept no changes are made to the radar display. Instead, three sets of distance based separation criteria are used that can be easily memorized. The headwind conditions determine which set of criteria are used. It is expected that procedural TBS is easier to implement but the benefits are smaller.

*Capacity Benefits of Time Based Separation*

Runway throughput simulation for DBS and TBS concepts show that part of the capacity lost in headwind conditions can be recovered using TBS. The pivot point lies at 5 kts headwind on the glideslope (wind at 1200 ft). How much capacity can be recovered depends on the fleet mix, because only distance based separation between wake pairs is reduced. Runway capacity becomes almost resilient to headwind when TBS with system support is applied in combination with a fleet mix of 70% heavy and 30% medium aircraft. This fleet mix is typical for Schiphol early morning arrivals. During other periods of the day, 10% - 20% of the aircraft are heavy and the remaining are medium aircraft. TBS with system support still provides benefits, however not all capacity lost due to headwind conditions can be recovered due to TBS only being used on wake pairs. In strong headwind conditions TBS with system support yields to approximately 1.5 AC/h – 2 AC/h extra compared to DBS.

The effect on the number of daily movements that can be accommodated have been studied for the period covering 2007 to 2014. In low headwind conditions TBS provides the same capacity as DBS. TBS with system support provides more capacity on a daily basis than DBS on 40% of the days in a year. On stormy days (average wind speed > 20 kts, 3% - 7% of days per year) TBS with system support yields 20 to 35 additional movements compared with DBS. On the same days, 10 to 20 additional movements can be accommodated using procedural TBS.

### 1.3 Reading Guide

In Chapter 2 the characteristics of the headwind conditions at Schiphol are discussed. The results of data analysis to determine the arrival capacity loss due to headwind are presented in Chapter 3. The two TBS concepts that have been analyzed to recover arrival capacity in headwind conditions are introduced in Chapter 4. Chapter 5 contains the results of the simulations that have been conducted to determine the effects of the TBS concepts on arrival capacity. The conclusions and recommendations of this study are given in Chapter 6.

## 2 Characteristics of Headwind Conditions

The benefits of TBS are dependent on the headwind conditions on the glideslope. However, a consistent dataset at these altitudes is not available. Therefore to provide indicative analysis on the headwind conditions experienced at Schiphol airport, METAR data (10m from surface) has been used.. The data covers the period between January 2007 and April 2015.In the following, wind conditions for the primary and secondary runways used for arrivals are analyzed first, followed by analysis of differences between runway, time of day and seasons.

### 2.1 Headwind conditions

Figure 2-1 shows the headwind on the primary and secondary runway used for arrivals versus the time in use. The average METAR headwind on the primary and secondary runway is 7 kts and 6.8 kts, respectively. For both runways in 80% of the time the headwind is less than 10kts, 30% of the time the headwind is 5 kts or less and 10% of the time there is a tailwind. However, there are significant differences between runways, as can be seen in Figure 2-2. Exposure to headwinds is lowest on runways 06, 36R and 36C. Approximately 10% of the time these runways are used, headwind exceeds 10 kts. Traffic using runways 18R or18C is exposed to headwinds of 10 kts or more 25% of the time the runways are used. Traffic arriving on runways 27 and 22 is exposed to the highest headwind speeds. These runways are used when there are stormy conditions, often related with a strong western wind direction. For runway 27 there are headwinds of 10kts or more occur 60% of the time and 10% of the time the headwind speed is 20kts or more. For runway 22 there headwinds speeds are even higher, 10kts or more 70% of the time and 20kts or more 40% of the time.

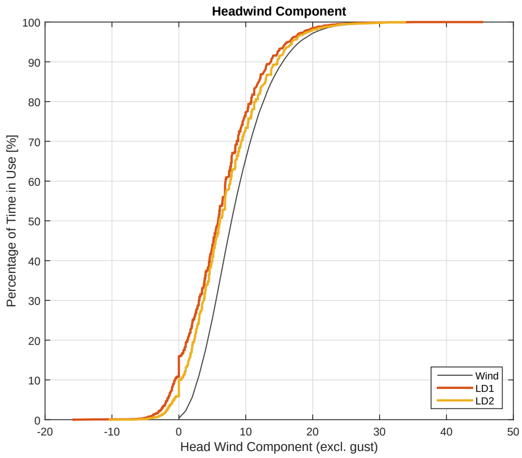



**Figure 2-1: Headwind component of the first (LD1) and second (LD2) runway.**

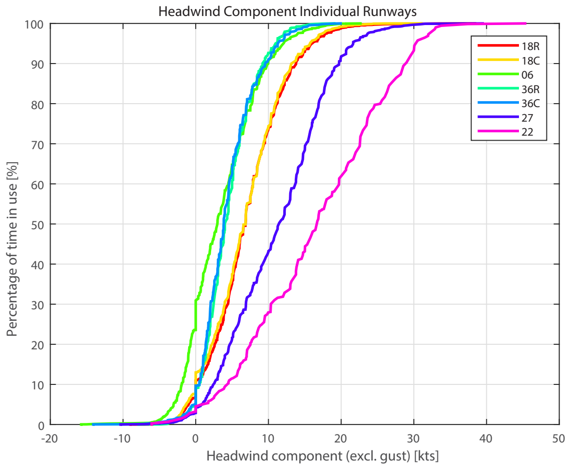



**Figure 2-2: Cumulative distribution of the headwind per individual runway.**

The percentage of the time each runway is in use and the mean headwind of every runway is shown in Table 2-1. In comparison to the main landing runways 18R and 06 the headwind speed is high for runways 22 and 27, however compared to runway 18R and 06 these runways are used only a small percentage of the time.

**Table 2-1: Runway use**

| Runway | Mean Headwind (at surface) | Time in Use |
|---|---|---|
| 06 | 4 kts | 30% |
| 36C | 4 kts | 4% |
| 36R | 5 kts | 11% |
| 18C | 7 kts | 12% |
| 18R | 7 kts | 53% |
| 27 | 12 kts | 12% |
| 22 | 18 kts | 1% |

## 2.2 Differences during the day

The headwind conditions change throughout the day. Figure 2-3 shows the distribution of the surface headwind speed during the day. Headwind speeds during the day are higher than headwind speed during the evening and night.

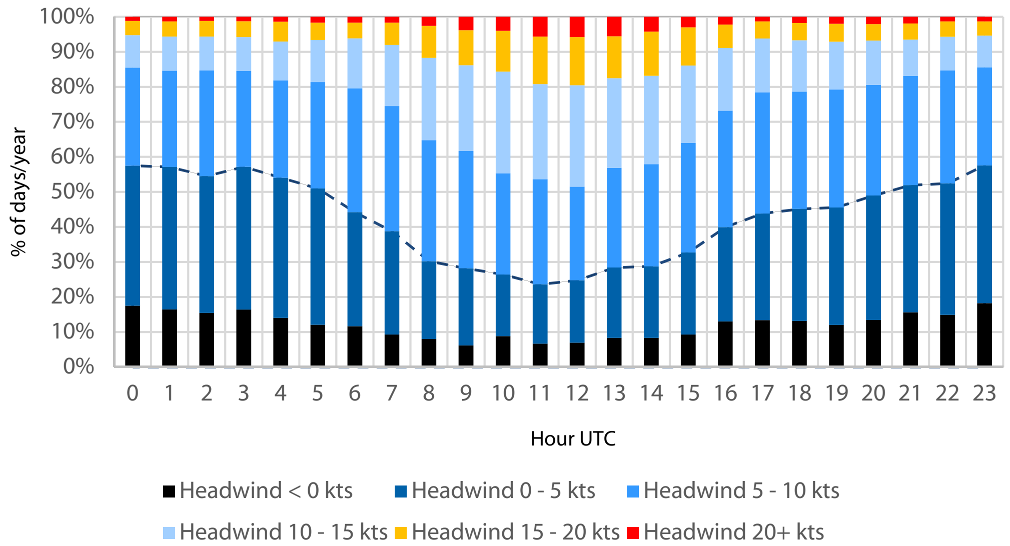



**Figure 2-3: Headwind distribution during the day.**

## 2.3 Seasonality

The surface headwind conditions also differ between seasons, as is shown in Table 2-2. Strong headwind conditions are most frequent in the winter. The percentage of the time strong headwinds are present during the summer, spring and autumn are significantly lower.

**Table 2-2: Headwind conditions per season**

| Season | > 20 kts | > 25 kts | > 30 kts |
|---|---|---|---|
| Autumn | 1.54% | 0.30% | 0.08% |
| Spring | 1.50% | 0.42% | 0.08% |
| Summer | 0.48% | 0.05% | 0.00% |
| Winter | 4.39% | 1.26% | 0.30% |

The headwind conditions per hour per season for the first landing runway are shown in Figure 2-4. For every season you see a similar trend as previously observed during the day, with strong headwinds being more frequent during the mid-part of the day. It can again be seen that strong headwind conditions are most frequent in the winter.

| | AUTUMN | | | SPRING | | | SUMMER | | | WINTER | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hour UTC | > 20 kts | > 25 kts | > 30 kts | > 20 kts | > 25 kts | > 30 kts | > 20 kts | > 25 kts | > 30 kts | > 20 kts | > 25 kts | > 30 kts |
| 0 | 1% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 2% | 1% | 0% |
| 1 | 1% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 3% | 1% | 0% |
| 2 | 1% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 3% | 1% | 0% |
| 3 | 1% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 3% | 1% | 0% |
| 4 | 1% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 4% | 1% | 0% |
| 5 | 1% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 4% | 1% | 0% |
| 6 | 1% | 0% | 0% | 1% | 1% | 0% | 0% | 0% | 0% | 3% | 1% | 0% |
| 7 | 1% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 3% | 1% | 0% |
| 8 | 2% | 1% | 0% | 3% | 0% | 0% | 0% | 0% | 0% | 4% | 2% | 0% |
| 9 | 3% | 1% | 0% | 4% | 1% | 0% | 1% | 0% | 0% | 5% | 2% | 1% |
| 10 | 3% | 2% | 0% | 4% | 1% | 0% | 2% | 0% | 0% | 6% | 2% | 0% |
| 11 | 4% | 1% | 0% | 5% | 0% | 0% | 2% | 0% | 0% | 9% | 3% | 1% |
| 12 | 5% | 1% | 0% | 6% | 2% | 0% | 2% | 0% | 0% | 9% | 2% | 0% |
| 13 | 5% | 1% | 0% | 7% | 2% | 0% | 2% | 0% | 0% | 7% | 2% | 1% |
| 14 | 3% | 1% | 0% | 4% | 1% | 0% | 3% | 0% | 0% | 6% | 2% | 1% |
| 15 | 2% | 1% | 0% | 4% | 1% | 0% | 2% | 1% | 0% | 4% | 1% | 0% |
| 16 | 2% | 0% | 0% | 2% | 0% | 0% | 1% | 0% | 0% | 4% | 1% | 1% |
| 17 | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 0% | 0% | 2% | 1% | 0% |
| 18 | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 0% | 0% | 4% | 1% | 0% |
| 19 | 1% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 5% | 2% | 0% |
| 20 | 2% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 5% | 2% | 1% |
| 21 | 1% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 5% | 1% | 0% |
| 22 | 0% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 4% | 1% | 0% |
| 23 | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 3% | 1% | 0% |

**Figure 2-4: Headwind conditions time of the day per season.**

## 3 Impact of Headwind on Arrival Capacity

Headwind on final approach reduces the ground speed of aircraft. Figure 3-1 shows the effect of headwind on the ground speed of a Boeing 777-200 on final approach at 1200 AGL (about 4 NM from the runway threshold). In a 25 kts headwind at ground level, the average ground speed is 25% lower than zero or low wind conditions. The distance based separation criteria are wind invariant, hence wind can have a significant effect on arrival capacity. To assess the impact of wind on the arrival capacity, meteorological, runway, and track data covering November 2010 to October 2013 have been analyzed.

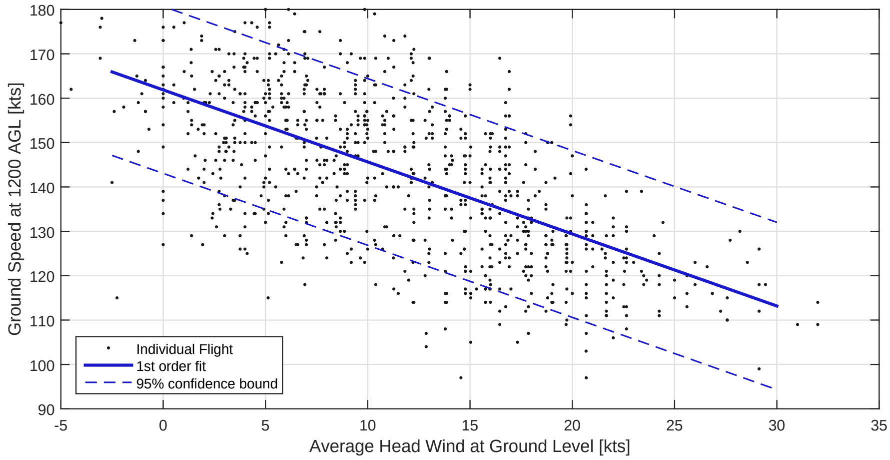



**Figure 3-1 Effect of headwind on ground speed of a Boeing 777-200 at 1200 ft AGL.**

### 3.1 Impact on the landing interval

Figure 3-2 shows the distribution of the landing interval at selected surface headwinds. The landing intervals increase as the headwind speed increases. The modes of the distribution (maximum value) shift to the right. The right tails of the distributions are not affected as headwind does not affect the landing interval if traffic is not closely spaced. Table 3-1 summarized the impact on the modes of the distributions.

**Table 3-1 Impact on Landing Interval**

| Condition | Landing Interval | AC/h |
|---|---|---|
| < 0 kts | 95 s | 38 |
| 00 – 10 kts | 98 s | 37 |
| 10 – 20 kts | 104 s | 34 |
| 20 – 30 kts | 111 s | 32 |

### 3.2 Impact on the minimum in-trail distance on approach

Figure 3-3 shows the distribution of the separation margin at selected surface headwinds. The separation margin is defined as the minimum in-trail distance on final approach minus the distance based separation criterion. Headwind has no significant effect on separation margin. The shift of the mode is < 0.1 NM. This implies that the increase of the landing interval can be related to lower ground speed and that only to a very small extent the capacity loss in strong headwinds is compensated by reduced in-trail distance.

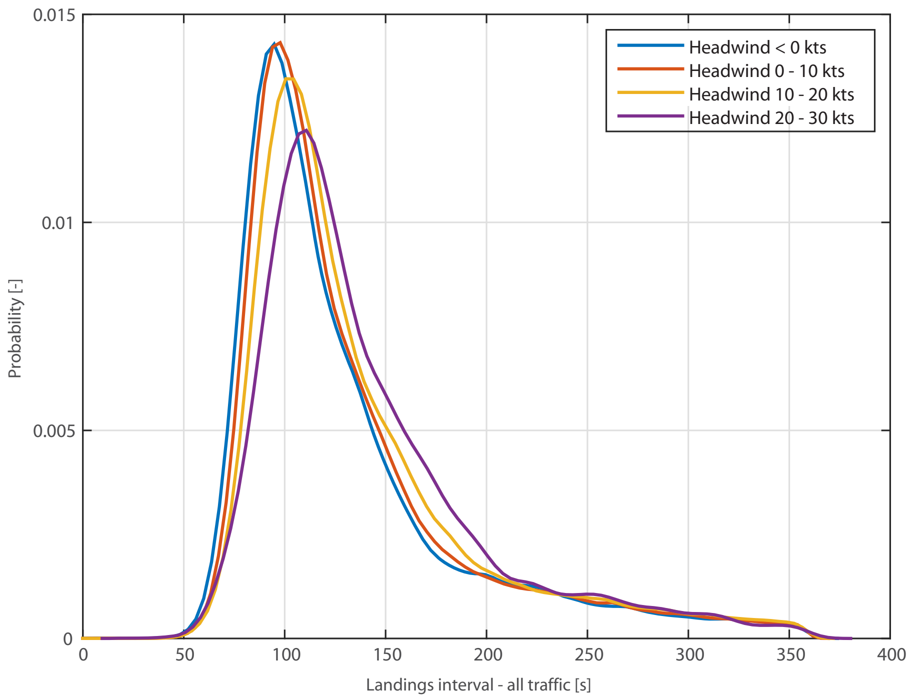



**Figure 3-2 Landing interval distribution as a function of headwind.**

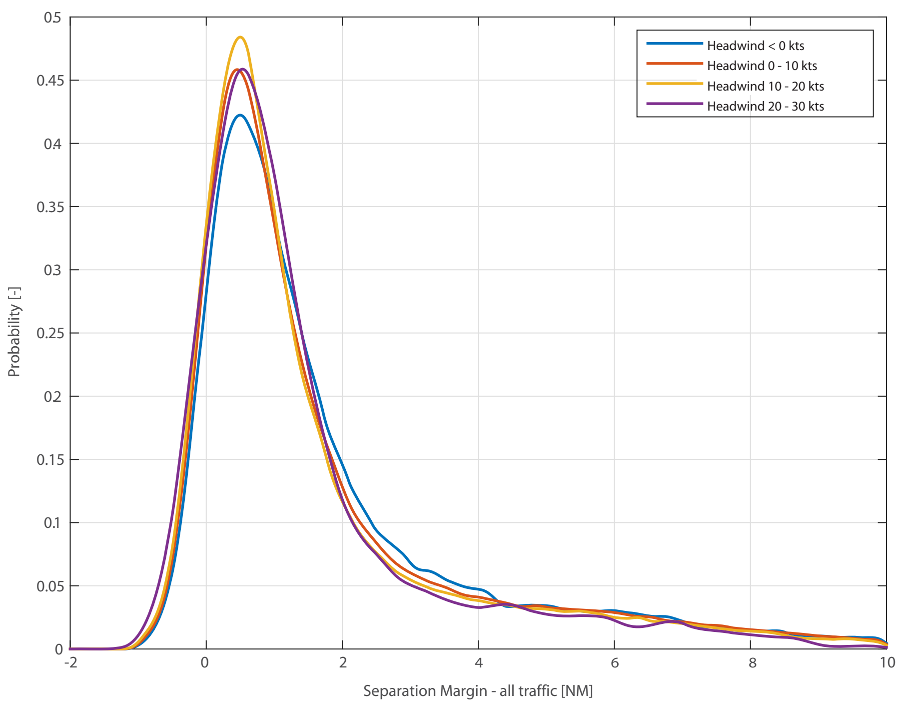



**Figure 3-3 Landing interval distribution as a function of headwind.**

### 3.3 Impact on runway capacity

The impact of headwind on the runway capacity is determined for all flights where the separation margin is between 0.1 NM and 0.9 NM and between -0.1 NM and 0.1 NM. The former gives realistic values of the runway capacity. The latter gives theoretical values where all movements are delivered to perfect separation. Figure 3-4 shows the absolute and relative effect of headwind on the capacity. There is a linear relationship between headwind and runway capacity. Approximately every 5 kts one movement is lost. A 25 kts headwind results in a 15% decrease in runway capacity, compared to zero headwind conditions.

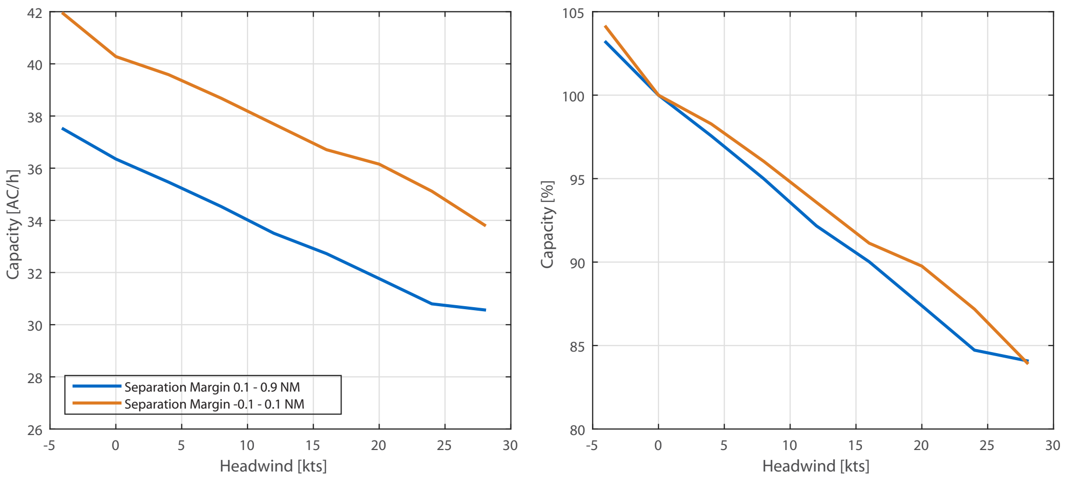



**Figure 3-4 Impact of headwind on average runway capacity.**

The effect on wake and non-wake pairs is shown in Figure 3-5. The effect on wake and non-wake pairs is similar.

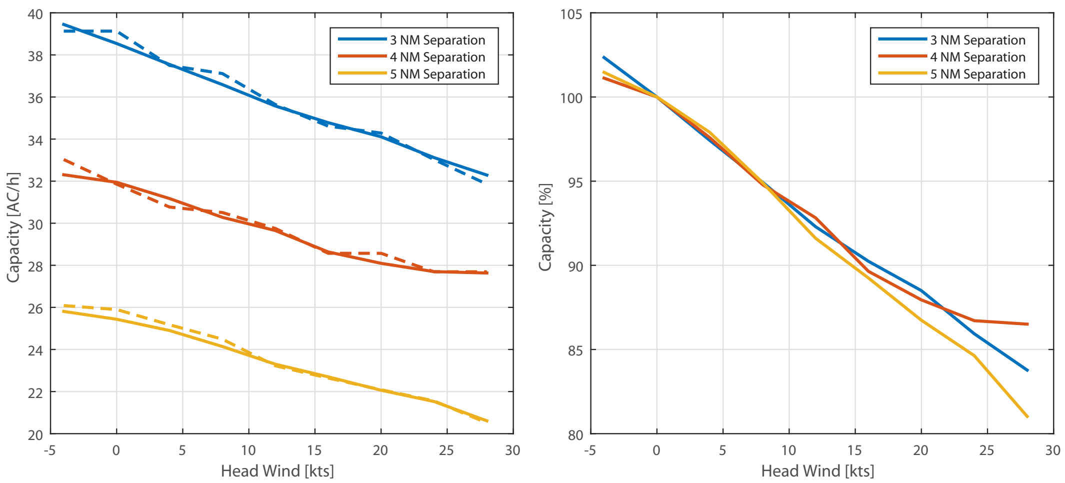



**Figure 3-5 Effect of headwind per wake turbulence category (sep. margin 0.1 – 0.9 NM)**

The effect of headwind on the runway capacity has also been analyzed statically using generalized linear models. The analysis shows confirms the trends observed in the figures above:

- One kt headwind results in a capacity loss of -0.2 AC
- Differences between all possible wake and non-wake pairs are non-significant or small

The analysis also showed that capacity of runway 22 is approximately 5 AC/h lower than for other runways. This is due to the infrastructure (e.g., no rapid exits) constraining aircraft by runway occupancy and acceptations of speed instructions to optimize the sequence. Therefore benefits of TBS for this runway may be limited.

Combining the headwind speed distributions (Chapter 2) and the effect of headwind on runway capacity, the impact of headwind on an annual basis can be determined. Figure 3-6 shows the result for the first landing runway (left) and for runway 27 (right).

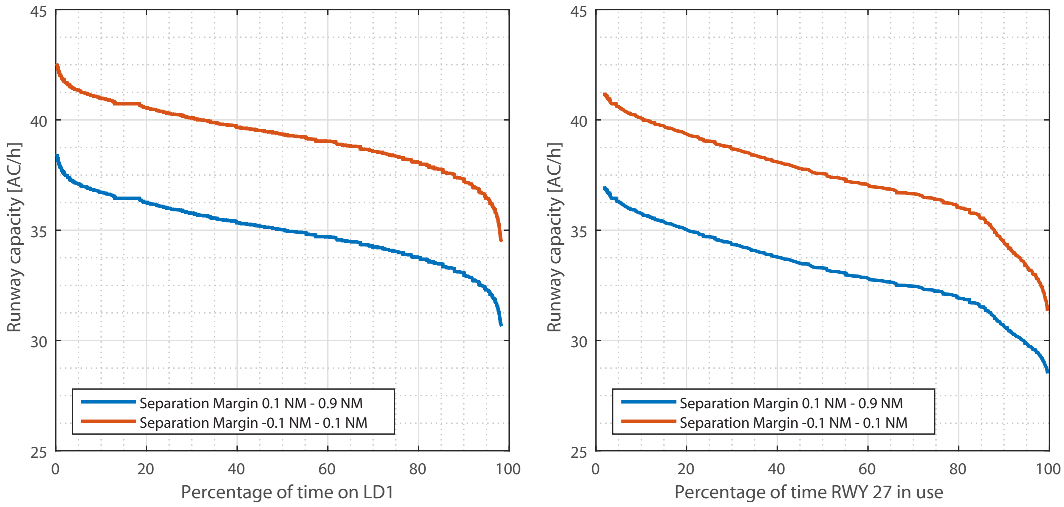



**Figure 3-6 Annual impact of headwind on average runway capacity.**

## 3.4 Limited number of runways that can be used for arrivals

Wind conditions may limit the number of runways that can be used for arrivals. Figure 3-7 shows the percentage of the days in a year when two runways were used for arrivals per 10 minute period. Five arrivals peaks can be identified. During arrival peaks, there are usually two runways in use for landing, however there are days only one runway was in use. This can have multiple causes, including the prevailing wind conditions. To assess if the use of only one runway can be attributed to wind, the prevailing conditions are compared to the wind envelope for the use of two runways for arrivals.

*Wind Envelope*

The wind envelope describes all the wind conditions in which two runways have been used for arrivals. Figure 3-8 shows the wind envelope. The wind vector is decomposed into the west-east and south-north components. The color is a measure for the frequency two runways have been used under these conditions in an arrival peak. In the In the yellow area, two runways have been used in these conditions almost all the time. In the dark blue area, only one runway has been used for arrivals.

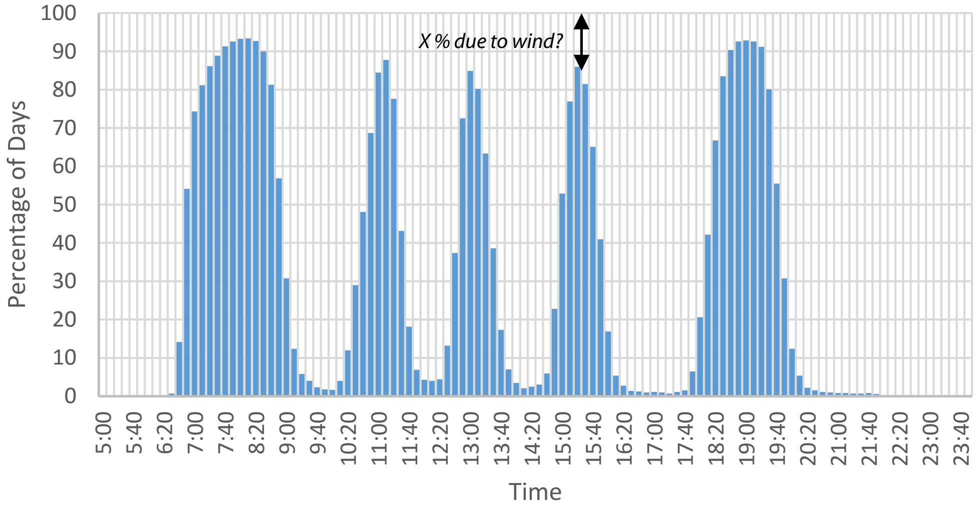



**Figure 3-7: Percentage of days two runways used for landings.**

For the period covering 2007 to 2015, wind conditions have been checked against the wind envelope for those periods where only one runway was used and use of two runways was expected. The red crosses in Figure 3-8 represent the days only one runway was used and wind was the likely cause. Wind conditions that inhibit the use of two runways are Northwesterly and Southwesterly storms, with wind speeds up to 30 kts excluding gusts. For 2014 and 2015 there was a clear link between days flagged as limiting by the wind envelope and news articles about heavy storms affecting Schiphol, see Appendix A - Storms. On average there are 8 days per year that only one runway can be used for arriving traffic, due to wind conditions.

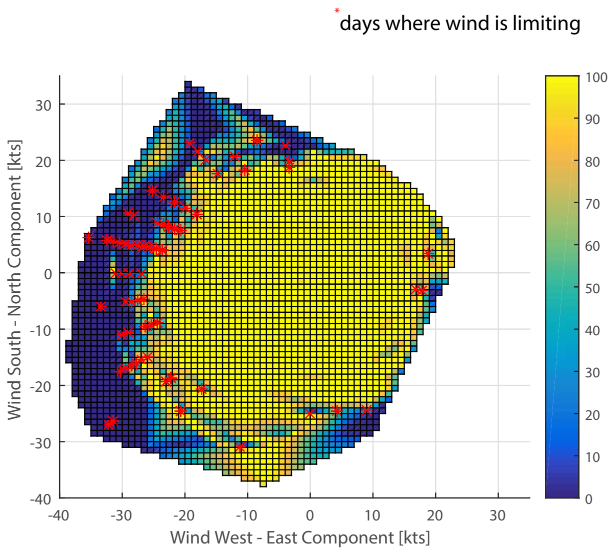



**Figure 3-8: Wind envelope showing where wind is limiting.**

The number of days where the wind is limiting per season (on average) are:

- Spring 2 days/year;
- Summer 1 days/year;
- Autumn 1 days/year;
- Winter 4 days/year.

Percentage of the time that wind is limiting on runways per peak, based on duration QRC:

- Peak 1 “first arrival peak” 0.5% (230 min/year)
- Peak 2 “late morning” 0.6% (140 min/year)
- Peak 3 “early afternoon” 0.7% (110 min/year)
- Peak 4 “late afternoon” 1.3% (280 min/year)
- Peak 5 “evening arrival peak” 0.5% (170 min/year)

# 4 Time Based Separation Concepts

Time-based separation (TBS) on final approach is a concept to provide arrival capacity resilience in headwind conditions. As shown in Chapter 3, arrival capacity is lost in headwind conditions when applying distance based separation (DBS). In the TBS concept, wake turbulence time based separations are used. From these time based separations, distance separations are computed based on prevailing winds along the glideslope. The distance separation between wake pairs is reduced in headwind conditions, hence compared to DBS runway capacity is increased.

In this study two TBS concepts have been studied. A procedural TBS and a TBS concept with system support, comparable to the Heathrow TBS concept. The main difference between both concepts is the level of system support to apply the TBS distances. The following two sections describe the TBS concepts and derivation of the wake turbulence time based separations.

## 4.1 Time Based Separation

The TBS concept is based on SESAR's Operational Service and Environment Definition for Time Based Separation for Arrivals [1] and the TBS concept implemented at London Heathrow.

The following generic concept description is taken from Ref. [4] by Morris, Peters, and Choroba on the validation of the TBS concept at London Heathrow.

### 4.1.1 Generic Concept Description

The TBS Concept involves changing the separation rules on final approach from distance based separations to time based separations. There is a need to facilitate delivery to time based separation constraints by the final approach and tower controllers. This is achieved through the provision of separation indicators displayed on the extended runway centerline of the final approach controller radar display and the tower runway controller air traffic monitor display, and changing the controller separation/spacing procedures to take into account the use of the separation indicators in supporting the arrival delivery on final approach.

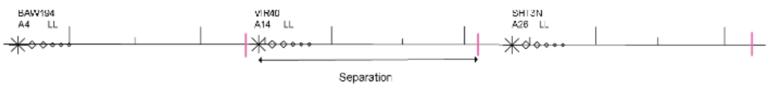



**Figure 4-1 Example of Separation Indicators on Final Approach**

The wake turbulence time based separations have been derived from the distance based separations taking into account the ground speed profile of aircraft on the final approach glideslope in low headwind conditions. The diversity of airspeed profiles flown on final approach makes the derivation more complex. This is the case for the procedural airspeed profiles prior to landing speed stabilization, as well as the airspeed profiles employed during landing stabilization in relation to the aircraft type, landing weight and other factors. These result in a multiplicity of time spacings associated with each distance based separation in the low headwind conditions.

To manage this complication, a reference airspeed profile is used to establish the reference time based separations in low headwind conditions. This reference airspeed profile is applied to the prevailing glideslope wind conditions to calculate the TBS distance to be displayed by the separation indicator. The actual airspeed profile of the follower aircraft under TBS will still vary, but only in the same way that it varies under DBS today. Therefore, the variation in time spacing under TBS will be no different to that under DBS in low wind conditions, and for TBS this time spacing for a particular airspeed profile is stabilized across headwind conditions. In this way the diversity of airspeed profiles employed on final approach is accommodated without the need to explicitly take into account the airspeed profile intent of the aircraft.

The TBS distance is to be applied from the follower aircraft merging on to final approach until the lead aircraft crosses the runway landing threshold in the same way as for distance based separation.

The low headwind conditions proposed is a minimum of 5 kts in order to provide additional spacing in the low, still and tail wind conditions in which pilot reported wake turbulence encounters are most prevalent for distance based separations.

The reference airspeed profile is to be representative of the local airspeed procedures of the aerodrome. For the generic concept a reference landing stabilization airspeed of 150 kts IAS is proposed. The impact of the runway elevation and glideslope angle on the true airspeed profile and resulting ground speed profile is to be taken into account when establishing the reference time based separations.

Generic reference time separations have been established by applying the wake turbulence distance based separations for the ICAO wake categories, applied to the runway landing threshold. These are for a 5 kt headwind on the glideslope over the spacing to the runway landing threshold. This is for a reference airspeed profile of 170 kts IAS to 6 DME, reducing to 150 kts IAS by 5 DME, and flying steady landing stabilization airspeed of 150 kts IAS to the runway landing threshold on a 3 degree glideslope and an 80 ft runway elevation. For spacing minimum pairs, 60 seconds is proposed to provide sufficient time for the runway occupancy time of the lead aircraft.

**Table 4-1 Generic Time Based Separations**

| DBS | Follower | | | |
|---|---|---|---|---|
| **Leader** | Super | Heavy | Medium | Light |
| Super | 3 NM | 6 NM | 7 NM | 8 NM |
| Heavy | 3 NM | 4 NM | 5 NM | 6 NM |
| Medium | 3 NM | 3 NM | 3 NM | 5 NM |
| Light | 3 NM | 3 NM | 3 NM | 3 NM |

| TBS | Follower | | | |
|---|---|---|---|---|
| **Leader** | Super | Heavy | Medium | Light |
| Super | 60 s | 145 s | 167 s | 189 s |
| Heavy | 60 s | 98 s | 122 s | 145 s |
| Medium | 60 s | 60 s | 60 s | 122 s |
| Light | 60 s | 60 s | 60 s | 60 s |

### 4.1.2 Schiphol Concept

The airspeed profile at Schiphol is different from the reference speed profile used in the generic concept description. To determine the wake turbulence time separation minima for Schiphol the same procedure as described above is followed, however using the local procedural airspeed profile and distance based separation minima. The AIP the Netherlands states:

- ATC will initiate speed reductions below 220 IAS.
- When established on ILS: maintain 160 kts IAS until 4 NM before threshold.
- Speed > 220 KT accurate within 10 kts; speed < 220 kts accurate within 5 kts.

For a 5 kts mean headwind at 4 DME the indicated airspeed is equal to the groundspeed. A 160 kts ground equates to a 22.5s per NM conversion (3600 / 160 = 22.5) for the distance based separations. The time based separation are given in Table 4-2.

**Table 4-2 Wake Turbulence Time Based Separations - Schiphol Concept**

| DBS | Follower | | | |
|---|---|---|---|---|
| **Leader** | A380 | Heavy | Medium | Light |
| Super | - | 6 NM | 7 NM | 8 NM |
| Heavy | - | 4 NM | 5 NM | 6 NM |
| Medium | - | - | - | 5 NM |
| Light | - | - | - | - |

| TBS | Follower | | | |
|---|---|---|---|---|
| **Leader** | Super | Heavy | Medium | Light |
| Super | - | 135 s | 158 s | 180 s |
| Heavy | - | 90 s | 113 s | 135 s |
| Medium | - | - | - | 113 s |
| Light | - | - | - | - |

Only for wake pairs time based separations are given. TBS is only used on wake pairs. Procedures for non-wake pairs are remain unchanged, i.e. distance based separation is equal to minimum radar separation (MRS).

### 4.1.3 Calculate Time Based Separation Distance

The TBS distance for wake pairs is calculated using the prevailing winds on the glide slope. In this study the wind at 4 DME (1200 ft AGL) is used. Table 4-3 gives TBS distances at selected headwinds.

**Table 4-3 TBS Distances for selected headwinds**

| Headwind (kts) on approach | TBS Distance [NM] | | | | |
|---|---|---|---|---|---|
| | H - H | H – M, M - L | H – L, S - H | S - M | S - L |
| 5 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 |
| 25 | 3.5 | 4.4 | 5.3 | 6.1 | 7.0 |
| 45 | 3.0 | 3.8 | 4.5 | 5.3 | 6.0 |

*S = Super, H = Heavy, M = Medium, L = Light*

The TBS distance between wake pairs remains equal or larger than the MRS. In this study 3 NM and 2.5 MRS are used. Separation distances between non wake pairs are the same as under DBS (i.e., 3 NM or 2.5 NM MRS).

## 4.2 Procedural Time Based Separation

In the procedural TBS concept no changes are made to the radar display to display the TBS distances to the controller. Instead, three sets of distance based separations are used that can be easily memorized. The distance based separation have been calculated using the wake turbulence time based separations.

In a 25 kts headwind the TBS distances between all wake pairs are reduced by 0.5 NM or more. In the procedural TBS concept, a 0.5 NM reduction is applied to distance based separations between wake pairs. In a 45 kts headwind the TBS distances between all wake pairs are reduced by 1 NM or more. In the procedural TBS concept, a 1 NM reduction is applied to distance based separations between wake pairs.

In the procedural TBS concept the separation distances are as follows:

- if headwind at 1200 ft < 25 kts, the existing DBS criteria are used:

| Distance [NM] | **Follower** | | | |
|---|---|---|---|---|
| **Leader** | Super | Heavy | Medium | Light |
| Super | 3 | 6 | 7 | 8 |
| Heavy | 3 | 4 | 5 | 6 |
| Medium | 3 | 3 | 3 | 5 |
| Light | 3 | 3 | 3 | 3 |

- if headwind at 1200 ft >= 25 kts, separation for wake pairs is reduced by 0.5 NM relative to the existing DBS:

| Distance [NM] | **Follower** | | | |
|---|---|---|---|---|
| **Leader** | Super | Heavy | Medium | Light |
| Super | 3 | 5.5 | 6.5 | 7.5 |
| Heavy | 3 | 3.5 | 4.5 | 5.5 |
| Medium | 3 | 3 | 3 | 4.5 |
| Light | 3 | 3 | 3 | 3 |

- if headwind at 1200 ft >= 45 kts, separation for wake pairs is reduced by 1.0 NM relative to the existing DBS:

| Distance [NM] | **Follower** | | | |
|---|---|---|---|---|
| **Leader** | Super | Heavy | Medium | Light |
| Super | 3 | 5 | 6 | 7 |
| Heavy | 3 | 3 | 4 | 5 |
| Medium | 3 | 3 | 3 | 4 |
| Light | 3 | 3 | 3 | 3 |

The effect of procedural TBS on capacity will be smaller than TBS with system support. The separation distance only change at 25 kts and 45 kts headwind and the same reduction is applied for all separation distances between wake pairs, hence those aircraft pairs with large wake separations will have additional separation compared to TBS with system support.

# 5 Effect of Time Based Separation on Capacity

The effects of the TBS concepts described in Chapter 4 on runway capacity have been studied using a runway queuing model. The simulations give insight in the effect of TBS on hourly runway capacity as a function of fleet mix and headwind in comparison to DBS.

Using the simulation results and meteorological, runway use, and fleet data covering the period 2007 to 2014, the effect of the TBS concepts on the number of movements that can be accommodated per day is determined. Subsequently, the effect of TBS on runway capacity has been studied for two cases: stormy days with headwinds on ground exceeding 20 kts and early morning arrivals with a 70 to 80% heavy aircraft fleet mix.

## 5.1 Simulation Scenarios

The TBS and DBS concepts that have been simulated are listed in Table 5-1. The TBS concept with system support and the DBS concept have been simulated for 2.5 NM and 3 NM MRS. Currently, the MRS at Schiphol is 3 NM, although in the future the MRS may be reduced to 2.5 NM. In this chapter the effects of changing separation rules from distance based to time based on capacity are analyzed. Therefore the TBS concepts are compared to the DBS baseline concepts with the same MRS. Lowering the MRS results in higher runway capacity for both the TBS and DBS concept. A comparison between DBS with 3 NM and 2.5 NM MRS is made in Appendix B.

**Table 5-1 Simulation Scenarios**

| Scenario | Baseline |
|---|---|
| Time Based Separation 3 NM MRS | Distance Based Separation 3 NM MRS |
| Time Based Separation 2.5 NM MRS | Distance Based Separation 2.5 NM MRS |
| Procedural Time Based Separation 3 NM MRS | Distance Based Separation 3 NM MRS |

## 5.2 Runway Queuing Model

Figure 5-1 gives a schematic overview of the runway queuing model. The model simulates the sequencing and separation of traffic and the final approach phase. Traffic is separated at 4 NM from the runway threshold. The actual distance between two aircraft when the leading aircraft is at 4 NM from threshold, is determined by the separation concept, aircraft wake categories, and additional spacing that is applied on top of the separation distance.

*Additional Spacing*

The distance between aircraft at 4 NM from threshold is in most cases different from the distance separation due to separation accuracy and additional spacing that is applied deliberately by the controller to ensure separation is maintained in the last 4 NM to the runway threshold. A statistical model is used to determine the actual distance between aircraft when the leading aircraft is at 4 NM from the runway threshold. This model has been derived from meteorological and radar tracks data. The additional spacing is drawn randomly from probability distributions. Figure 5-2 gives an example of such a probability distribution together with the target spacing (i.e., separation distance). On average the actual distance between aircraft at the metering point (4 DME) is more than the required separation distance.

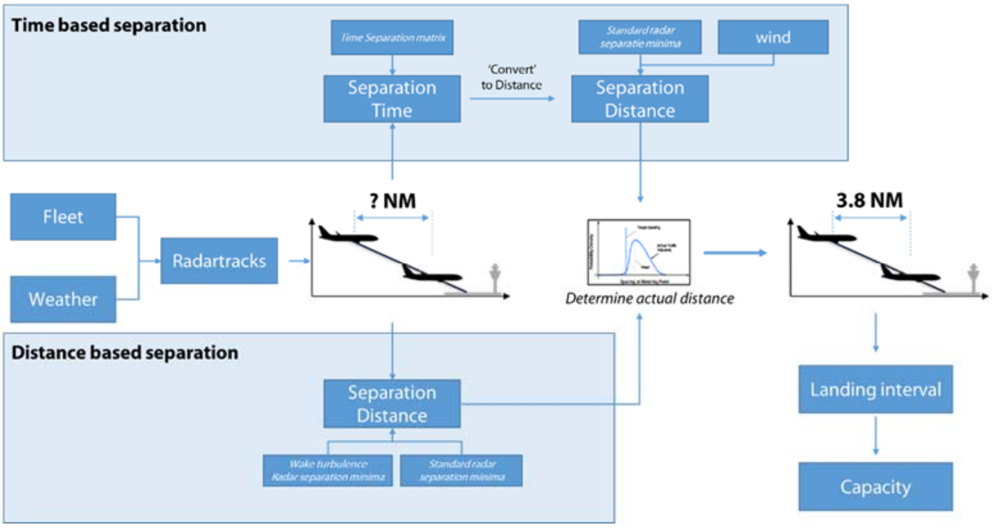



**Figure 5-1 Schematic overview runway queuing model.**

*Input - Output*

Model inputs include distance or time separations, fleet mix, wind conditions. Model output includes the landing interval.

The model has been calibrated and validated by simulating the Schiphol operation under DBS at various headwind and comparing the simulated runway capacity to the actual runway capacity as determined in Chapter 3.

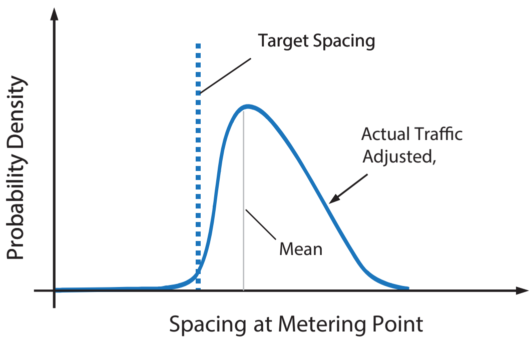



**Figure 5-2 Spacing at Metering Point.**

## 5.3 Fleet mix and Headwind Conditions

Using the runway queuing model the runway capacity has been determined for the TBS and DBS concepts as a function of fleet mix and headwind. Three fleet mixes have been selected, based on fleet distribution over the day that is shown in Figure 5-3.

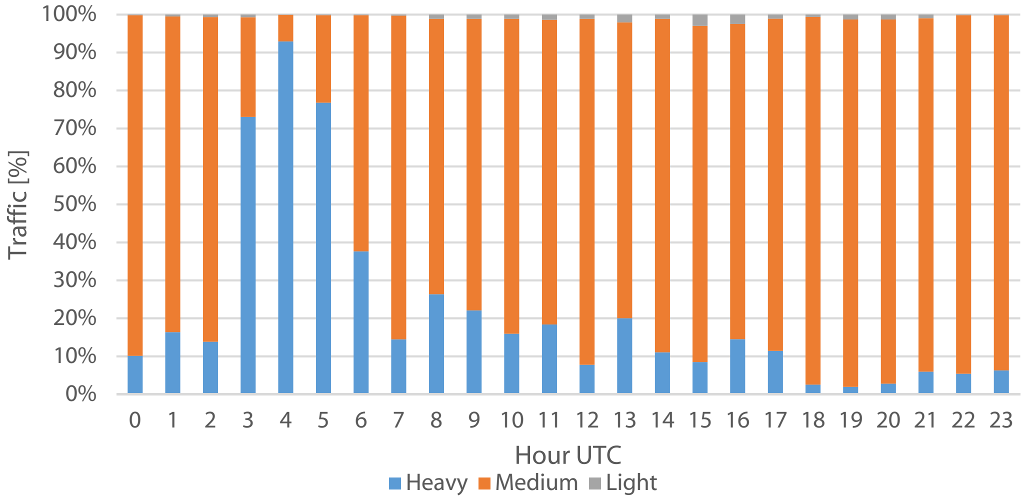



**Figure 5-3 Wake Turbulence Category distribution over the day 2007-2014.**

The three fleet mixes are:

- 10% heavy aircraft, 90% medium aircraft – representative for day, night and evening
- 20% heavy aircraft, 80% medium aircraft – representative for day
- 70% heavy aircraft, 30% medium aircraft – representative for the early morning arrivals

The headwind at ground level (10 m AGL) ranges between -4 kts (tailwind) up to 28 kts. The wind profile of the atmospheric boundary layer (surface to around 2000 m) is generally logarithmic in nature and can be approximated using the log wind profile equation that accounts for surface roughness. The logarithmic wind profile is given by:

$$v_2 = v_1 \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)}$$

Where, the reference wind speed v1 is measured at height h1, v2 is the wind speed at height h2 and z0 is the roughness length. In the simulations a surface roughness value of 0.0024 m, representative for open terrain with a smooth surface, e.g. concrete, airport runways, mown grass etc. is assumed. Wind is measured at 10 m AGL.

## 5.4 Effect on runway capacity

Figures 5-4 through 5-8 show the runway capacity for the DBS and TBS concepts as function of the headwind for three different fleet mixes. TBS concepts provide higher runway capacity than DBS in strong headwind conditions. The pivot point for TBS with system support lies around 5 kts headwind as this is the value where TBS distance = DBS distance; in winds higher than 5 kts the TBS distance is smaller than the DBS distance. The TBS concept affects the distance separation between wake pairs. Hence, the capacity benefit depends on the percentage of heavy aircraft and the headwind. For a fleet mix with 10% heavy aircraft the capacity benefit is marginal. For a strong 25 kts headwind at ground level, a capacity benefit of 1 AC/h is expected. In a fleet mix with 20% heavy aircraft the capacity benefit increases to 1.5 AC/h – 2 AC/h for a 25 kts headwind at 10 m AGL.

For a fleet with 70% heavy aircraft and 30% medium aircraft, a capacity benefit of 1 AC/h can already be expected for a 12 kts headwind. The capacity benefit increases almost linearly with headwind up to 5 AC/h for 28 kts headwind. Also, the runway capacity has become almost resilient to headwind. Headwind impacts runway capacity by no more than 2 AC/h under TBS, compared to 7 AC/h for DBS.

In low headwind (headwind < 5 kts at 1200 ft AGL) and in tailwind conditions. The TBS distance between wake pairs is more than the DBS separation criterion. Therefore, in these conditions runway capacity of the TBS concepts with system support is lower than in the DBS concept. For a fleet mix with 10% or 20% heavy the effect is marginal. For a fleet mix with 70% heavy aircraft, there is a 1 AC/h hour loss for a 4 kts tailwind.

Runway capacity for the procedural TBS concept is equal to the DBS concept up to the point 25 kts headwind at 1200 ft AGL At this point, distance separation between all wake pairs is reduced by 0.5 NM. At 45 kts the distance separation between all wake pairs is again reduced by 1 NM. Because of the stepwise reduction of the distance separation, the capacity benefit is lower compared to TBS with system support. For a fleet mix 10% heavy aircraft the effect is marginal. For a fleet mix with 20% heavy aircraft a 1 AC/h is expected for a headwinds 10 m AGL of 25 kts. For a fleet with 70% heavy aircraft, there is a 2 AC/h for a 25 kts headwind 10 m AGL.

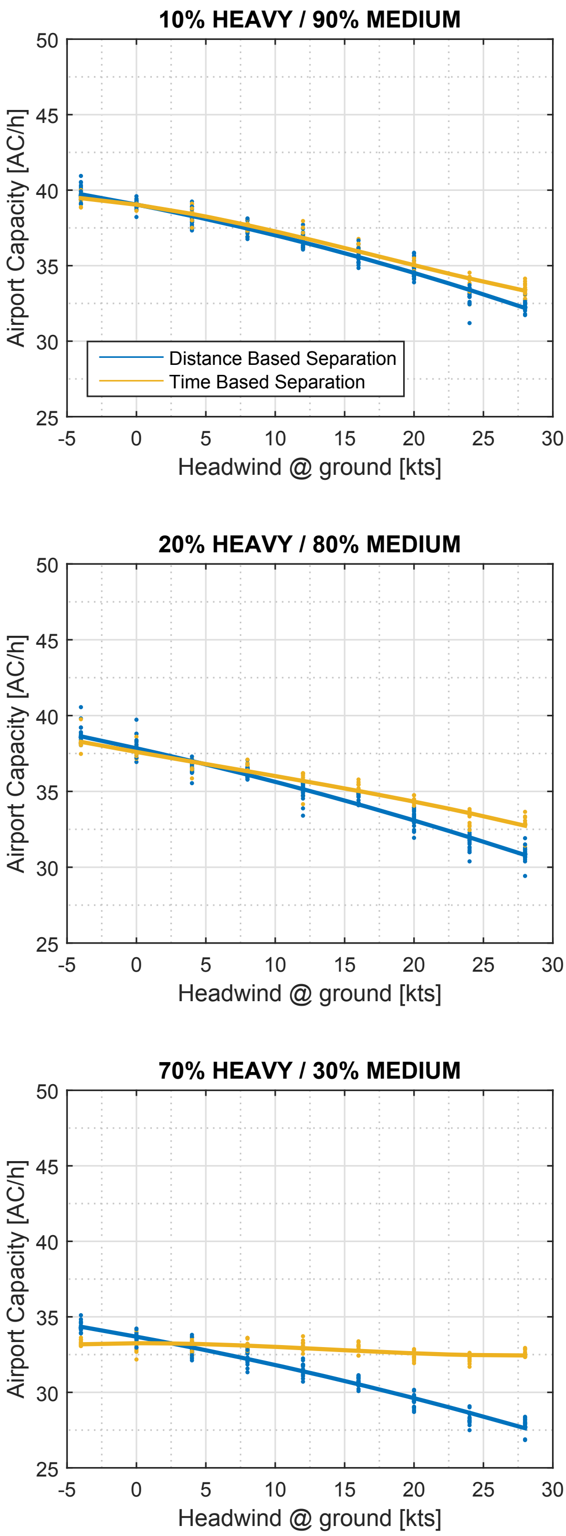



**Figure 5-4 DBS vs TBS with system support, 3 NM MRS.**

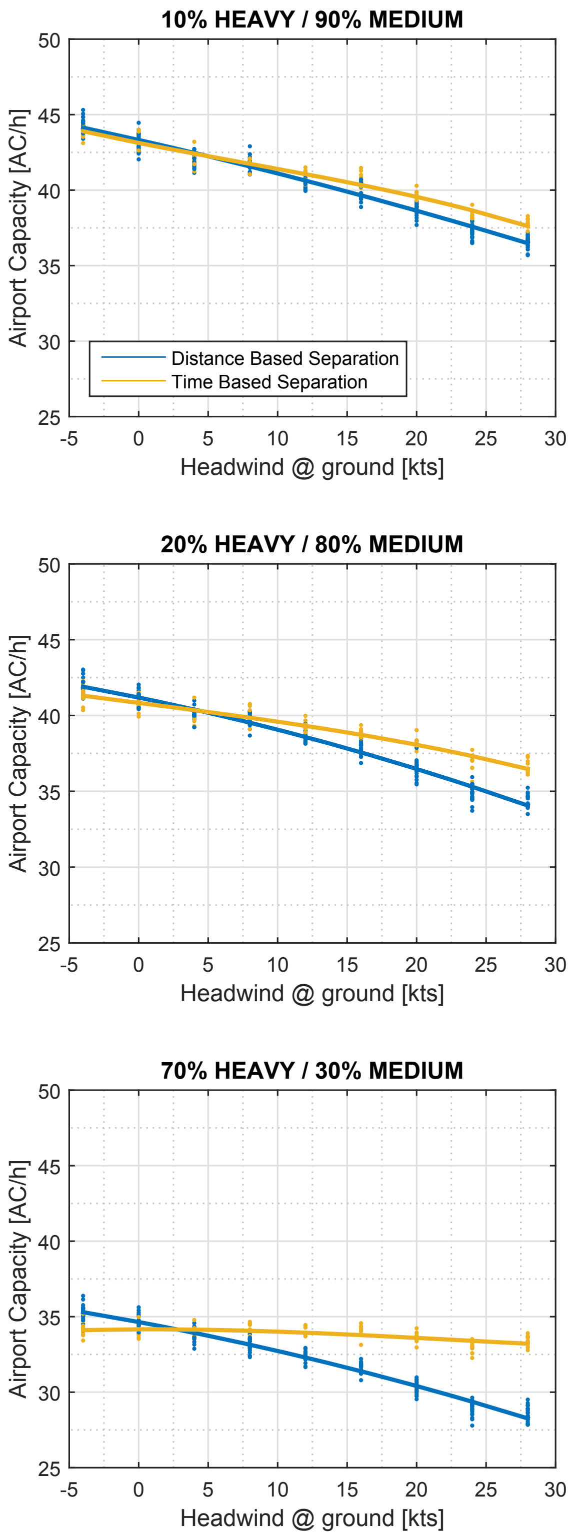



**Figure 5-5 DBS vs TBS with system support, 2.5 NM MRS.**

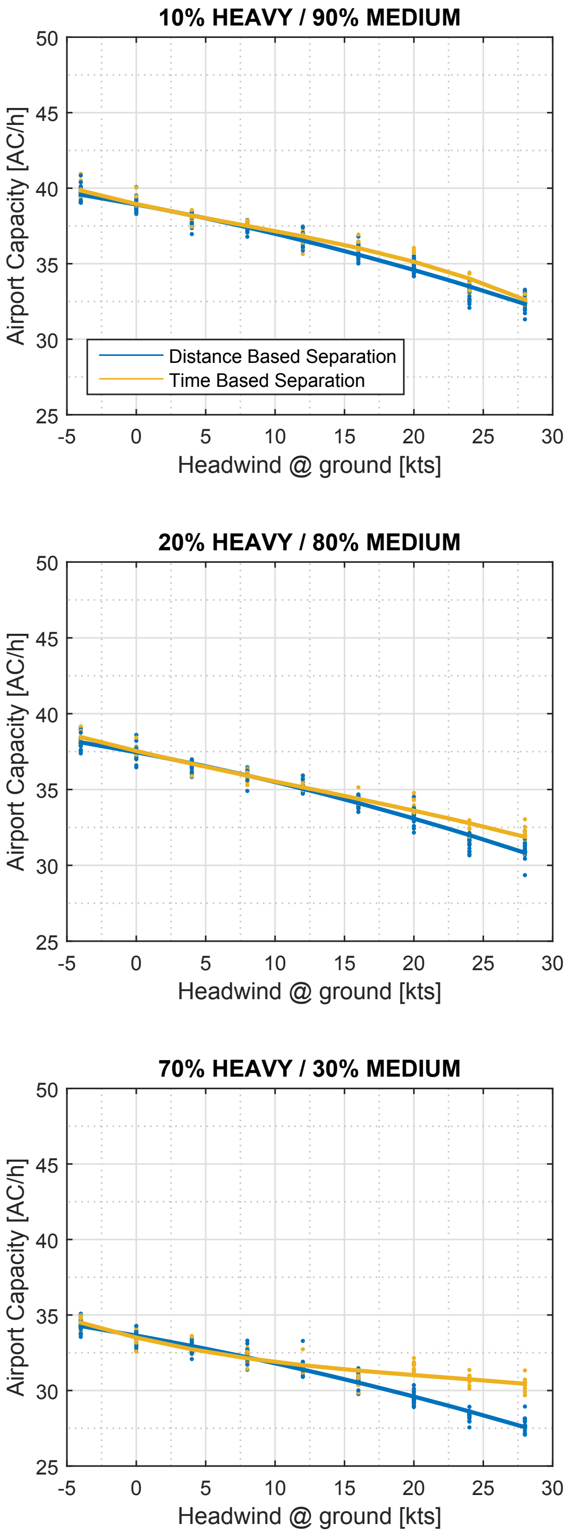



**Figure 5-6 DBS vs procedural TBS, 3 NM MRS.**

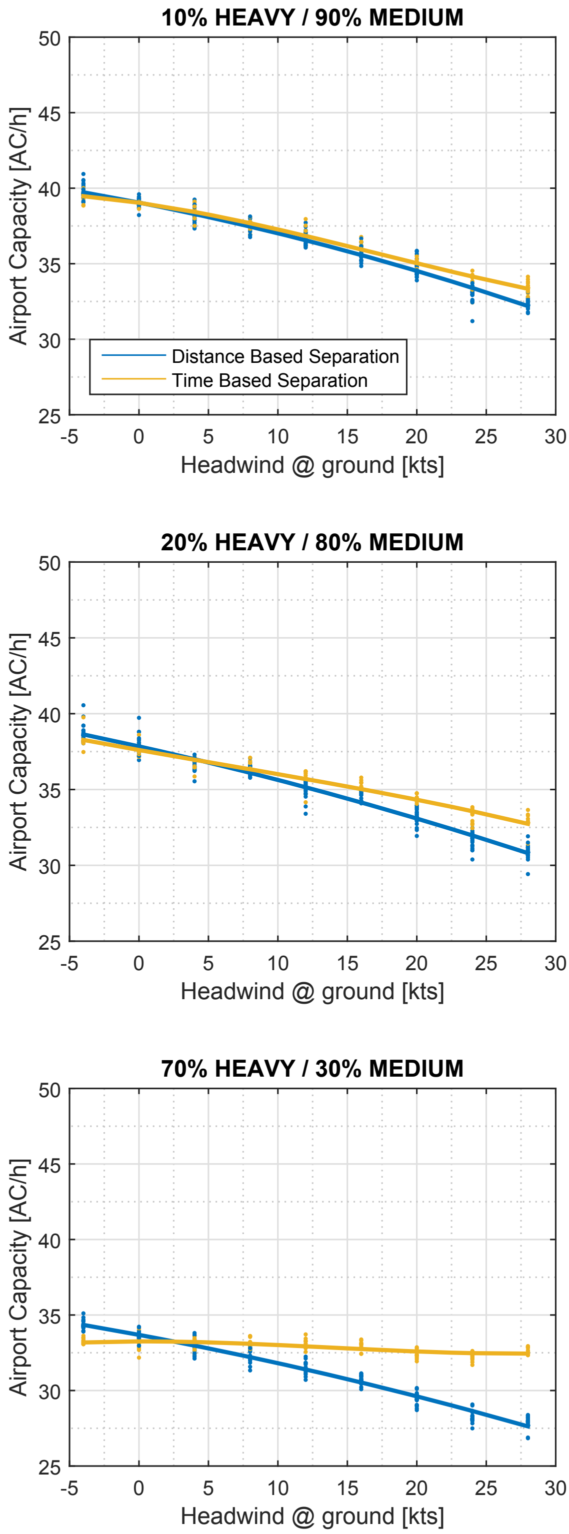



**Figure 5-7 DBS vs TBS with system support, 3 NM MRS – same as Fig 5-4.**

## 5.5 Effects per day

Using the above simulation results and meteorological, runway use, and fleet data covering the period 2007 to 2014, the effect of the TBS concepts on the number of movements that can be accommodated is determined.

Figure 5-8 shows the effect of the two TBS concepts on capacity per day (see Appendix C for the cumulative distributions). The night period, use of runway 22 and mixed mode runway use have been excluded. Overall, all three TBS concepts have a positive effect on the runway capacity.

The TBS concepts with system support (2.5 NM or 3 NM MRS) perform similar. The effects of TBS and 2.5 MRS are bigger, because in the baseline (DBS) runway capacity is higher. The relative size of the effects for TBS with 2.5 NM and 3 NM are equal. The effect ranges from -15 to +35 movements per day. The TBS concepts with system support can also have a negative effect on capacity. On these days headwinds are low. In most cases where a negative effect on capacity was observed there was a slight tailwind, increasing the distance separation between wake pairs.
Procedural TBS results in up to 15 additional movements. Table 5-2 shows the percentage of days per year an increase in the daily capacity can be expected.

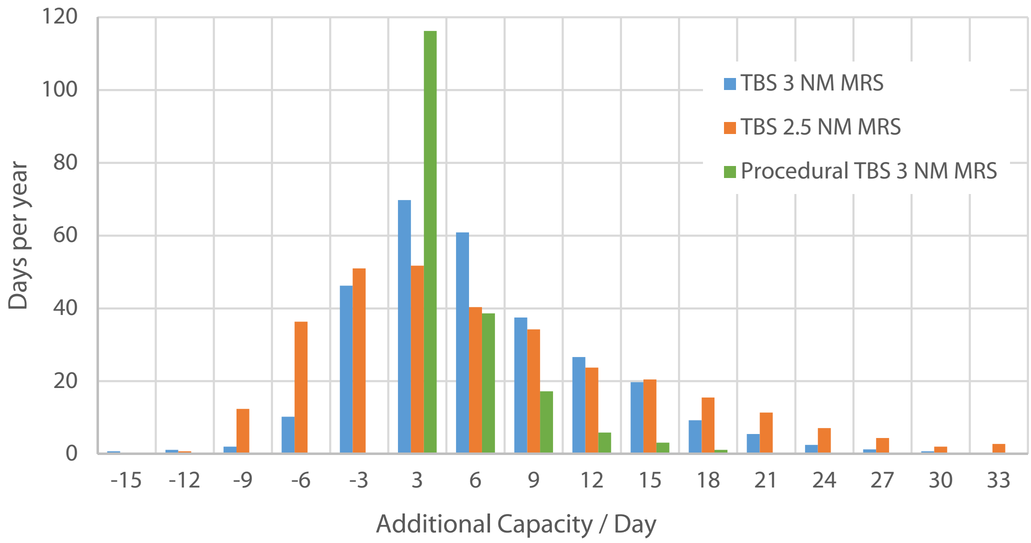



**Figure 5-8 Effect of TBS concepts on capacity / day**

**Table 5-2 Effect TBS concepts percentage of days per year (2007-2014 average)**

| Δ movements | TBS 3 NM MRS | TBS 2.5 NM MRS | Procedural TBS 3 NM MRS |
|---|---|---|---|
| -5 or less | 3% | 12% | 0% |
| +5 or more | 41% | 42% | 16% |
| +10 or more | 20% | 25% | 4% |
| +20 or more | 3% | 7% | < 1% |

Figure 5-9 shows the effect of the TBS concepts on capacity vs. the average wind speed. On days with high wind speeds (mean wind speed >= 20 kts), 20 to 35 additional movements can be accommodated using TBS with system support. With procedural TBS 10 to 20 additional movements can be accommodated on these days.

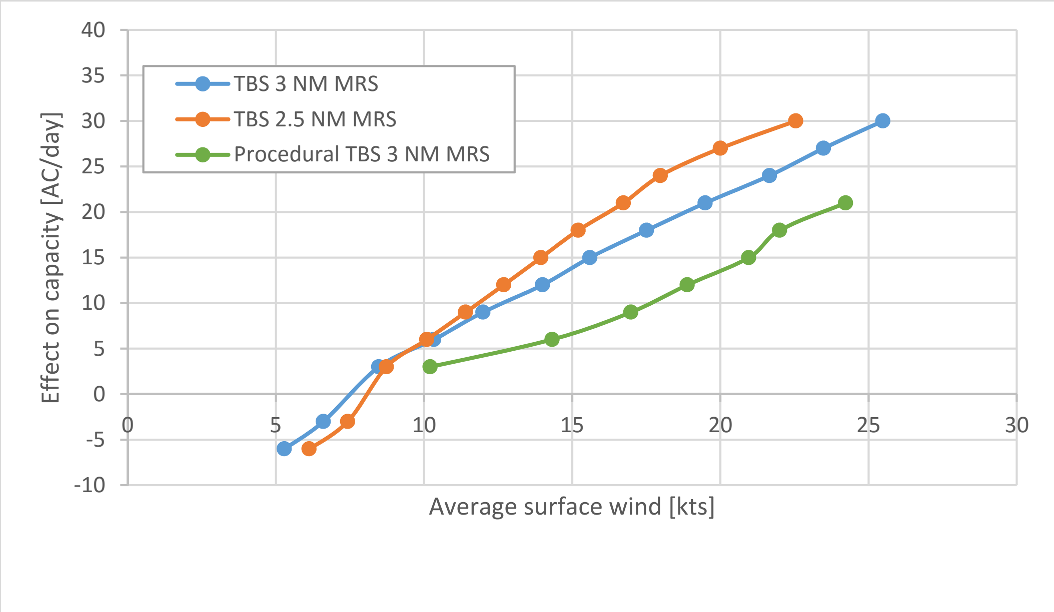



**Figure 5-9 Effect of TBS capacity vs. average wind speed**

## 5.6 Case Studies

Based on the simulation results two cases have been selected to demonstrate and quantify the benefits of TBS in a more operational context:

- Stormy days
- Early morning arrival peak – comprising of 70-80% heavy aircraft

### 5.6.1 Stormy days

In stormy conditions, headwinds at ground level easily exceed 20 kts. Based on the runway simulation results a significant capacity benefit can be expected in these conditions.

*Storm - November 15 2015*

On November 15 2015 a storm passed over the Netherlands. This day is studied in more detail to quantify the effect of TBS on the runway capacity on a stormy day. The wind direction varied between 240° and 250° with wind speeds between 24 and 31 kts (excl. gusts). The storm picked up in the evening of November 14 and died out around 18:00 UTC on November 15. During the storm runway 27 was in use for landings, except for a 40 minute period in which runway 22 was used. During arrival peaks 18R was also used. For runway 18R no capacity benefits are expected, due to the low headwind speed and limited number of aircraft using this runway under the prevailing wind conditions. Therefore it is not studied any further.

Based on the runway simulations results, typical fleet distribution, meteorological observations (METAR), it is expected that between 5:00 UTC (6:00 LT) and 18:00 UTC, TBS with system support could have catered for approximately 16 more movements on runway 27 than DBS. With procedural TBS, 8 additional movements could have been accommodated.

*Top 80 stormy days*

In the top 80 stormy days in the period covering 2007 to 2014 (ranked by average wind speed) on average 22 and 12 additional movements can be accommodated with TBS and procedural TBS respectively.

### 5.6.2 Early morning arrivals

Delay of aircraft in the morning can cause snowballing of delays during the day. High sustainability of the runway capacity can help reduce delays. The early morning arrivals are characterized by the high percentage of heavy aircraft. The TBS concept provides resilience to headwind. The effect of TBS increases with the percentage of heavy aircraft in the fleet. Figure 5-10 shows the runway capacity sustainability curves for the TBS and DBS concepts for the early morning arrivals (70-90% heavy traffic) for the period covering 2007-2014. In the DBS concept, runway capacity is lost due to headwind. In the TBS concept with system support, runway capacity is almost resilient to headwinds. Compared to DBS runway capacity, TBS with system support yields higher runway capacity 70% of the time. Capacity is increased by 1 AC/h or more in 20% of the time and 1 to 2 AC/h or more in 10% of the time with a maximum of 4 AC/h. In tailwind conditions or low headwind conditions (approx. 20%) there is an average loss of 0.4 AC/h with a maximum of -1 AC/h. Compared to DBS, procedural TBS yields higher runway capacity 30% of the time and a 1 AC/h or more increase 5% of the time with a maximum of 2 AC/h.

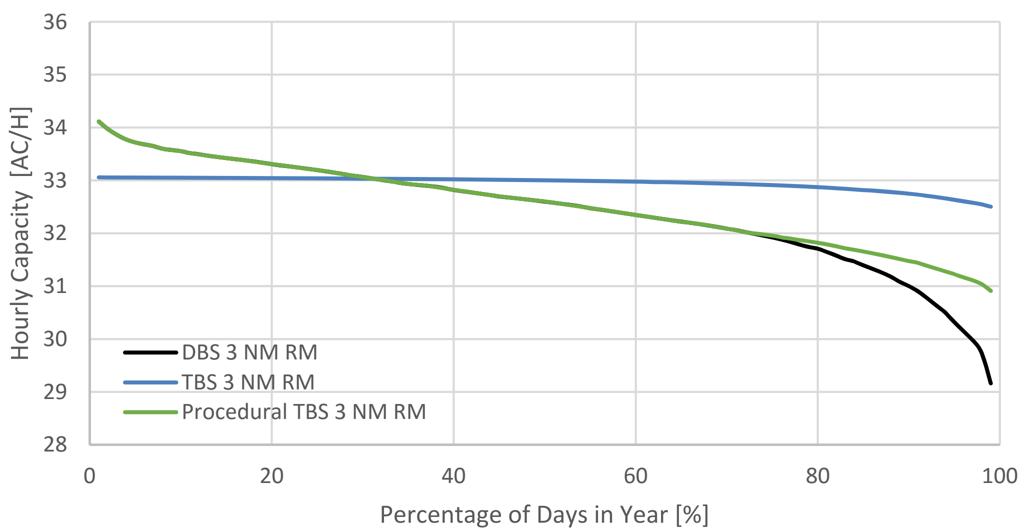



**Figure 5-10 Sustainability graph runway capacity for TBS and DBS concepts during early morning arrivals (70-90%) heavy traffic**

## 5.7 Benchmark London Heathrow Time Based Separation Operations

TBS benefits for London Heathrow have been studied as part of SESAR P6.8.1, see reference 1. The results show that in stronger headwind conditions TBS is expected to recover on average one to two movements per hour in comparison to DBS. For some hours the model predicted both TBS concepts to recover up to a maximum 5 movements per hour. TBS is in operation at London Heathrow since March 2015. NATS determined the benefits seen to date. A cross all wind conditions on average one additional movement per hour can be accommodated. In strong wind conditions three extra movements can be accommodated.

The results of the SESAR study and the results of this study (section 5.4 of this report) are in the same order of magnitude. The results of this study have also been discussed with NATS. It was concluded the results are very comparable and in line with expectations.

# 6 Conclusions and Recommendations

## 6.1 Conclusions

The main conclusions of this study are:

*Headwind conditions*

- On average a headwind of 7 kts is encountered at ground level on the primary and secondary runway. Headwinds of more than 10kts and 20kts are encountered 20% and 3% of the time, respectively.
- Traffic arriving on runways 27 (average surface headwind 12 kts) and 22 (average surface headwind 18 kts) is exposed to the highest headwind speeds.
- Strong headwind conditions are most frequent in the winter.
- On average there are 8 days per year that only one runway can be used for arriving traffic, due to wind conditions.

*Capacity loss due to headwind*

- In headwind conditions runway capacity is reduced at a rate of approximately 1 AC/h per 5 kts headwind at ground level.
- During stormy conditions (headwind > 25 kts or more), runway capacity is reduced by approximately 5-6 AC/h, equivalent to a capacity reduction of 15%.

*Effect of Time Based Separation on runway capacity*

- By using Time Based Separation on final approach part of the runway capacity, lost in headwind conditions can be recovered. How much capacity can be recovered depends on the fleet mix and TBS concept that is used. TBS with system support provides more resilience to headwind than procedural TBS.
- Approximately 40% of the days per year TBS with system support provides more capacity than DBS.
- During storms, on a daily basis, 20 to 35 additional movements can be accommodated with TBS compared to DBS. With procedural TBS 10 to 20 movements more can be accommodated compared to DBS.

## 6.2 Recommendations

The work done in this study has led to the following recommendations:

- The simulations results show that runway capacity can be increased by lowering the minimum radar separation from 3 NM to 2.5 NM. It is recommended to investigate the feasibility of reducing the minimum radar separation from 3 NM to 2.5 NM.
- The current study only focused on the capacity gains that can be achieved by implementing TBS, however it is recommended to study other aspects like for example how TBS will be implemented. Determining the wind at the glideslope and forecasting the wind are some examples of further studies.
- European Wake Vortex Re-categorization (RECAT-EU) is a new, more precise categorization of aircraft than the traditional ICAO one that is currently used at Schiphol. It aims at increasing airport capacity by redefining wake turbulence categories. It is recommended to perform a RECAT capacity study for Schiphol and to repeat the simulations conducted in this study with RECAT.

# 7 References


1. SESAR's Operational Service and Environment Definition for Time Based Separation for Arrival
2. COMMISSION IMPLEMENTING REGULATION (EU) No 716/2014 of 27 June 2014 on the establishment of the Pilot Common Project supporting the implementation of the European Air Traffic Management Master Plan
3. NATS TBS website, http://www.nats.aero/tbs/
4. Morris, Charles., Peters, John, Choroba, Peter, Validation of the Time Based Separation concept at London Heathrow Airport, Tenth USA/Europe Air Traffic Management Research and Development Seminar

# Appendix A - Storms

## Maart eindigt met lentestorm

Zeist - 31 maart 2015, 07:20

Een lentestorm veroorzaakte vandaag gevaarlijk weer in grote delen van het land en voor het noorden gold een waarschuwing voor extreem weer: code oranje. Het hardst waaide het vandaag op de Houtribdijk (Enkhuizen-Lelystad) met tijdelijk een zware storm (10 Bft) en een zeer zware windstoot van 120 km/uur. Lees hieronder nog eens rustig de feitjes over de storm terug.

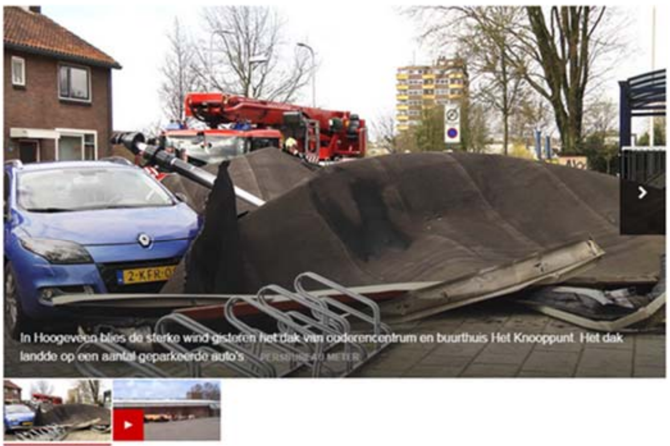
**Woensdag 1 april 8:33** Tijdens stevige buien zijn in de avond lokaal nog zwaardere windstoten opgetreden dan gisteren overdag. De zwaarste windstoten top-5 van 31 maart ziet er uiteindelijk als volgt uit:

1. Hoek van Holland: 134 km/uur
2. Houtribdijk (Dijk Enkhuizen-Lelystad): 120 km/uur
3. Lelystad: 117 km/uur
4. Gilze-Reijen (Noord-Brabant): 115 km/uur
5. Lauwersoog: 113 km/uur

http://nieuws.weeronline.nl/31-03-2015-live-blog-lentestorm/

## Stormschade bijna 10 miljoen euro

01-04-2015, 09:27 BINNENLAND



In Hoogeveen blies de sterke wind gisteren het dak van ouderencentrum en buurthuis Het Knooppunt. Het dak landde op een aantal geparkeerde auto's

Het Verbond van Verzekeraars becijfert de schade als gevolg van de storm van gisteren op bijna 10 miljoen euro. De meeste meldingen gaan over omgevallen bomen, weggewaaide dakpannen en rondvliegende takken en puin en waterschade.

http://nos.nl/artikel/2027994-stormschade-bijna-10-miljoen-euro.html

Het waait weer: stormschade overzicht van 10 januari

Datum: zaterdag 10 januari 2015 10:00

**Haaglanden** - Het weer laat haar aanwezigheid duidelijk merken: In de hele regio is overlast van storm en op sommige plekken gaan daardoor dingen kapot. Voornamelijk bomen en takken, maar ook dakplaten, geveldelen en schoorstenen ondervinden de gevolgen van de harde wind. Gedurende de dag plaatsen wij hier update's met foto's.



http://www.regio15.nl/

Storm(achtig)

Het is morgen opnieuw stormachtig met soms zware of zeer zware windstoten. Als het dan geen winter is, is het vaak dit weertype. En deze tijd van het jaar staat bekend als de donkere dagen voor kerst. De benaming is te danken aan onder ander het weertype. Vaak hebben we in deze tijd een westelijke stroming met veel bewolking en regen. Niet alleen het weer, maar ook de tijd van het jaar speelt een rol bij deze benaming. De lange nachten en de korte dagen. Dus de donkere dagen voor kerst.

http://www.pietsweer.nl/piets-blog/2014/stormachtig-3/


## Wind vertraagt een derde van vluchten op Schiphol

Gepubliceerd: 22 december 2014 11:24
Laatste update: 22 december 2014 17:04

**Ongeveer een derde van de vluchten op Schiphol heeft maandag vertraging ondervonden door de harde wind rond de luchthaven.**

Het oponthoud van de vertraagde vluchten varieerde van dertig tot zestig minuten, aldus een woordvoerder. Ook waren er enkele uitschieters. Maar er hoefden geen vluchten te worden geannuleerd.

De harde wind kwam uit een ongebruikelijke hoek, west-zuidwest. Daardoor blies de wind dwars op drie landingsbanen die in de richting noord-zuid liggen. Dat had gevolgen voor de start- en landingscapaciteit van Schiphol.

De luchthaven raadt passagiers aan zich via de website van Schiphol en die van vliegmaatschappijen op de hoogte te stellen van eventuele vertraging.

http://www.nu.nl

## Eerste najaarsstorm een feit


Vannacht heeft het voor de eerste keer deze herfst gestormd. Er was sprake van een uurgemiddelde van 9 Beaufort op station Hoek van Holland. Daarmee is de eerste najaarsstorm een feit. De storm ging gepaard met zware windstoten. De zwaarste windstoot werd gemeten in Hoek van Holland, dat was 108 km/uur.

De storm viel samen met een vrij hoog waterpeil, waardoor op veel plaatsen langs de kust sprake was van een verhoogde paraatheid van de hoogheemraadschappen. In Zeeland werd de Oosterscheldekering vannacht gesloten.

http://nieuws.weeronline.nl/weeronline-live-stormkracht-en-zware-windstoten/

## Van recordwarmte naar sneeuw in één week

Zeist - 8 januari 2014, 09:40

We beleefden de afgelopen dagen recordwarmte in Nederland. Niet eerder was het begin januari zo warm met 14,5 graden op maandag. Maar het weer staat op het punt te gaan veranderen met begin volgende week zelfs kans op echte sneeuw.

**Weerrecords afgelopen tijd**

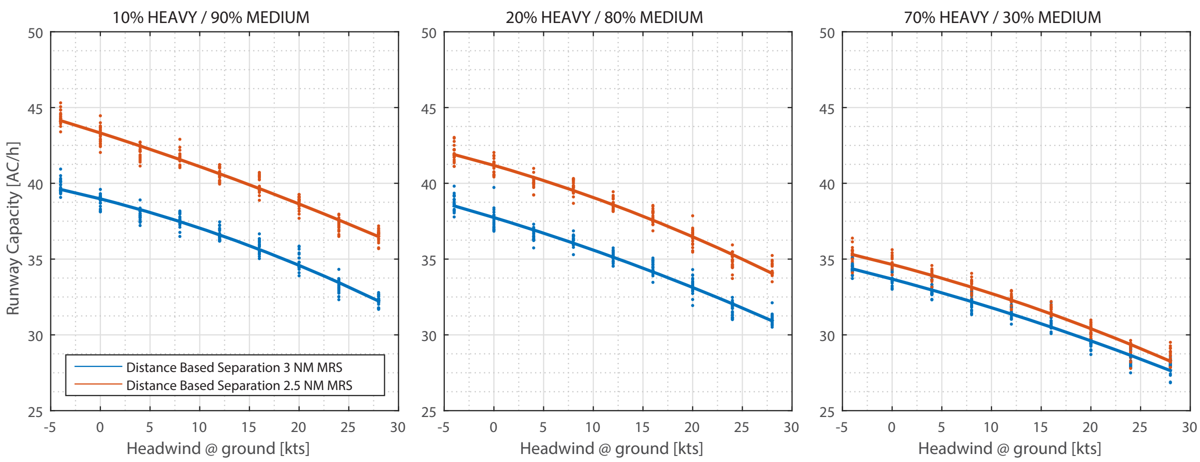
Verschillende weerrecords sneuvelden afgelopen tijd. Zo was vrijdag de warmste 3 januari ooit gemeten en leverde ook maandag 6 januari een dagrecord af. De 14,5 graden van maandag was zelfs de hoogste temperatuur ooit begin januari gemeten en de op één na warmste januaridag ooit. Dinsdag was Maastricht de koploper met de hoogste temperatuur ooit ergens in Nederland gemeten op 7 januari.

Behalve de temperatuur viel vooral de wind op. Regelmatig kwam het tot storm en zware windstoten.

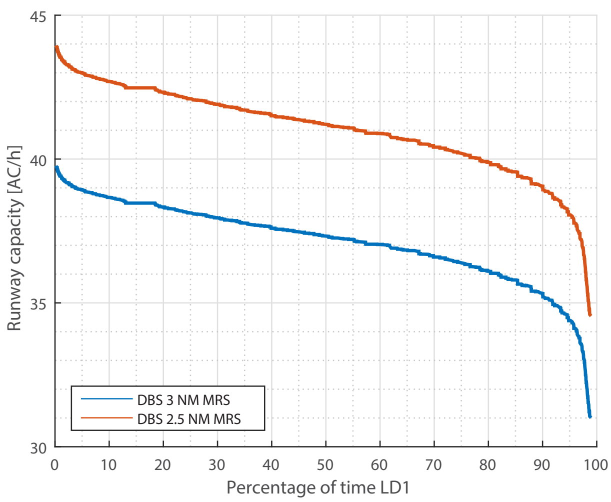
http://nieuws.weeronline.nl/recordwarmte-sneeuw-week/

## Appendix B – Effect of Minimum Radar Separation on Runway Capacity

In this study TBS concepts with 2.5 NM and 3 NM MRS have been analyzed. Reducing the MRS from 3 NM and 2.5 in the existing DBS concept will also result in a capacity increase. This increase in capacity is further described in this appendix. The figure below shows the capacity vs. the headwind for 2.5 NM and 3 NM MRS. All non-wake pairs are separated 2.5 NM from each other at 4 NM from the runway threshold. It is assumed the additional spacing applied by the controllers to maintain separation within 4 NM from runway threshold does not change as a result from lowering the MRS from 3 NM to 2.5 NM. Also the runway occupancy time is not considered a limiting factor. The percentage of heavy aircraft increases from left to right. Reducing the MRS, affects the separation between non-wake pairs only. Independent of the headwind, runway capacity is increased by 4.5, 3 and 1 AC/h for a fleet mix with 10%, 20% and 70% heavy aircraft, respectively.

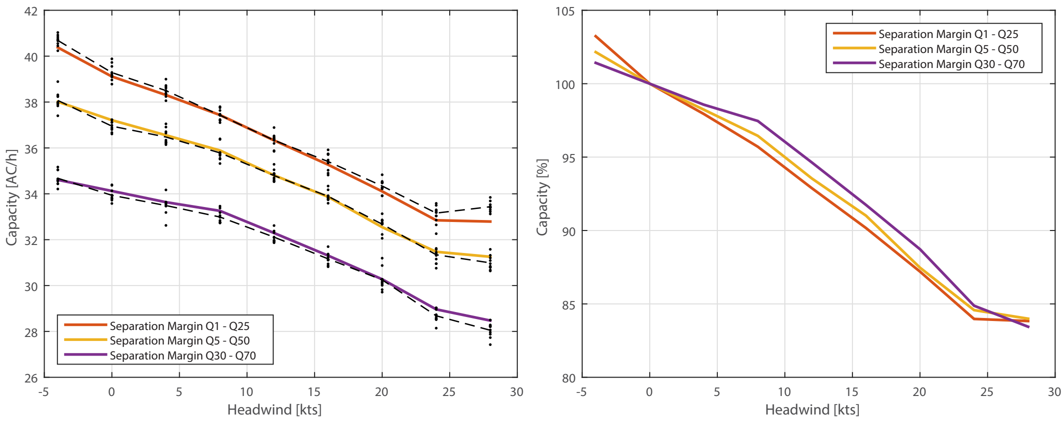



The figure below shows the average runway capacity as function of the headwind speed for Schiphol's fleet mix.



## Appendix C – Additional Simulation Results

### Validation of Runway Queuing Model




### Cumulative Distribution of the Additional Movements per Day