Airport capacity increase via the use of braking profiles

Jacek Skorupski *, Hubert Wierzbicki

Warsaw University of Technology, Faculty of Transport, Koszykowa 75, 00-662 Warszawa, Poland

A R T I C L E   I N F O

Article history:
Received 16 June 2015
Received in revised form 6 April 2016
Accepted 22 May 2016
Available online xxxx

Keywords:
Airport capacity
Air traffic
Braking profile
Aerodrome traffic management
Petri nets
Landing roll modeling

A B S T R A C T

Many airports are encountering the problem of insufficient capacity, which is particularly severe in periods of increased traffic. A large number of elements influence airport capacity, but one of the most important is runway occupancy time. This time depends on many factors, including how the landing roll procedure is performed. The procedure usually does not include the objective to minimize the runway occupancy time. This paper presents an analysis which shows that the way of braking during landing roll has an essential impact on runway throughput and thus on airport capacity. For this purpose, the landing roll simulator (named ACPENSIM) was created. It uses Petri nets and is a convenient tool for dynamic analysis of aircraft movement on the runway with given input parameters and a predetermined runway exit. Simulation experiments allowed to create a set of nominal braking profiles that have different objective functions: minimizing the runway occupancy time, minimizing noise, minimizing tire wear, maximizing passenger comfort and maximizing airport capacity as a whole. The experiments show that there is great potential to increase airport capacity by optimizing the braking procedure. It has been shown that by using the proposed braking profiles it is possible to reduce the runway occupancy time even by 50%.

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1. Introduction

The aircraft crew typically carries out four tasks. These are:

- flight management, i.e. navigation and maintaining aircraft control,
- communication management related to all processes of information exchange, both internally within the crew members and also with the air traffic controller,
- system management, consisting of the necessary monitoring or operating of technical on-board flight support systems,
- task management, consisting of monitoring and prioritizing tasks and assigning necessary resources, such as crew time.

These tasks do not refer directly to air traffic management (ATM). However, the aircraft crew affects the realization of ATM services' tasks. For instance, air traffic safety and quality of the air traffic management process depend on the pilot's predictability, the calm and consequent execution of the controller's instructions, and, finally, on attention, vigilance and composure in case of an emergency. However, usually the pilot is passive in relation to ATM tasks.

In this paper we propose a model and a decision support system in which the pilot plays an active role in a task which is closely related to ATM. This task is runway capacity management. The pilot can select the braking force in such a way as to...
keep the runway occupancy time (ROT) as small as possible or so that occupancy time is compatible with the intentions of the air traffic controller. This problem is important in case of mixed operations because it allows for more departures between arrivals and also for reduction of departure queue length. It is also important when the volume of air traffic is close to the saturation value. However, the proposed method can be applied also to minimize noise, tire wear or to maximize passenger comfort. These issues are always important, even if (or perhaps especially if) the traffic is small and shortening of the ROT is not necessary. The method can be applied to any airport and for any type of aircraft.

1.1. Runway capacity

The airside capacity of an airport depends directly on the runway system capacity. This, in turn, depends on many factors, but the most important is the runway occupancy time (ROT). This time is the basis for determining the theoretical maximum runway throughput. A significant part of the runway occupancy time for landing operations falls on the landing roll, which is under consideration in this paper. The relations are (Sherry, 2009):

\[ T_{\text{max}} = \frac{3600}{\text{ROT}} \]  \hspace{1cm} (1)

where

- \( T_{\text{max}} \) – maximum runway throughput with continuous takeoff and landing operations, expressed in the number of operations per hour.
- \( \text{ROT} \) – the average runway occupancy time in seconds. This time depends on many factors, such as aircraft type, touchdown speed, touchdown point, selected runway exit, runway surface condition and many others. One of the key factors is the average aircraft speed between the touchdown point (which is random) and the runway exit point. This speed depends on the braking profile (BP), including the use of wheel brakes and the thrust reverser.

The maximum throughput \( T_{\text{max}} \), determined according to formula (1), is a theoretical concept because it ignores separations between the following landings and take-offs that are required by international regulations. However, it can be used for comparisons for: different airports, different ways of air traffic organization, and, finally, different braking strategies. As shown in formula (1), reducing the ROT for each individual takeoff or landing helps to increase the maximum runway throughput. In practice, we usually use the concept of the so-called practical runway capacity, which takes into account many random factors affecting airport traffic operations and the delays resulting from this. Regardless of the selected definition of capacity, the general relationship between runway capacity and runway occupancy time is the same (Horonjeff et al., 2010).

From the airport capacity point of view, the ideal situation is when the aircraft leaves the runway through the rapid exit located at the point where the aircraft reaches a speed that is appropriate to turn into the taxiway after applying maximal braking. Unfortunately, such airport geometry rarely takes place. This is due to the fact that different types of aircraft use the airport, for which exit points as referred to above are located in different places. In addition, this location of the exit taxiway carries the risk that the landing aircraft will not have enough room to slow down if any distortion takes place, such as a different touchdown point and delay in brake deployment. Therefore, very often the available runway exit points are located at a distance much larger than the ideal one as referred to above. In this situation, the method of implementing the braking procedure has great importance for the runway capacity. The model and decision support system as discussed in this paper are about finding the braking profile (BP) that will allow for safe braking and at the same time for minimizing the ROT for a given airport layout.

1.2. Literature review

Airport capacity management is one of the most frequently found topics in the literature on air transport management. It is discussed, for example, in Irvine et al. (2015), Gelhausen et al. (2013), Kalakou et al. (2014), Farhadi et al. (2014), Sölveling and Clarke (2014), Stelmach et al. (2006) and Balakrishna et al. (2010). These papers focus on various factors affecting airport capacity, e.g. aircraft speeds, traffic mix, separation minima, passenger operations, taxi-out times, etc. Relatively little is devoted to issues regarding runway occupancy time (Trani et al., 1996), and particularly the influence of what technique is used when the aircraft braking process is being carried out. Our paper tries to fill in this gap.

Automatic control of the aircraft, also in the phase of ground movement, finds its place in the literature. For example, Chen et al. (2013) proposed to control the plane’s movement in accordance with the trajectory determined on the ground by means of a adaptive dynamic backstepping algorithm. Similarly, Li et al. (2011) considered the stability of the braking aircraft track when the aircraft is equipped with an anti-skid braking system. The main emphasis in these papers, however, was put on correct mapping of the movement trajectory and not on operational issues, such as airport capacity, which are the main subject of our study.

In the literature, much attention is paid to avoiding skidding during braking, especially on wet surfaces or surfaces covered with snow. Yadav and Singh (1995) demonstrated that skid-free braking requires a variable braking force which has to be treated as a random variable. Cao et al. (2014) analyzed the impact of rainfall on various aspects of the movement of air-
craft, including the safety of the landing process. In our work we do not examine the issue of skidding, however, we take into account variable braking performance according to the state of the runway surface.

In this paper we will consider, inter alia, use of the thrust reverser to improve airport capacity. A similar issue was analyzed in Malaek and Parastari (2001). Our approach is, however, a significant extension of their work. We take into account runway exit points that are different than only the nearest exit taxiway. Besides, we take into account final speeds other than 0. This is particularly important when we are dealing with rapid exit taxiways. In addition, the method presented in the current paper allows to take into consideration additional movement criteria, which are very important for airport capacity, such as passing the intersection of runways. An important extension of the previous studies is to propose a different approach to controlling the braking force derived from the thrust reverser, i.e. from controlling the position of the reverser’s end plates to controlling the rotational speed of the low-pressure rotor with complete closure of the end plates (which is a typical structure and does not require rebuilding the engine control system).

The problems of braking on icy surfaces, including the use of a thrust reverser, are shown in more detail in Klein-Paste et al. (2012). Safety issues when landing on damaged surfaces were analyzed by Benedetto et al. (2014). There are also restrictions on the use of the thrust reverser, for instance, those related to the noise that is generated by this device. These issues were analyzed by Asensio et al. (2013). On the other hand, Filippone (2014) suggested a method of forecasting the noise caused by use of the thrust reverser. In our paper we consider this problem by proposing a selection of BP so that the noise is kept to a minimum.

Chen et al. (2012) pointed to the extremely important issue of uncertainty regarding the aerodynamic forces and moments which arise, for example, from a lack of information regarding the plane’s mass at touchdown, which may significantly change the parameters of the braking process. They propose the use of artificial neural networks in order to find a good approximation of these forces. In the current paper, we assume that these forces are known, but the design of the proposed computer tool allows for verification of the correctness of this assumption, and if it turns out to be wrong, to determine a new BP. In further studies it will be possible to take into account the results of Wang et al. (2014), which pointed to the parameters that have the greatest impact on potential problems with a long braking distance and which are known to the pilot of the landing aircraft. The problem of correctly determining an aircraft’s movement parameters that are necessary for optimization of its trajectory was also undertaken by Alligier et al. (2013). In turn, Liu et al. (2014) analyzed the impact of airport surface automation on airport capacity. Our work fits well with these considerations and extends them by including braking process automation, which has so far not been considered.

1.3. The landing aircraft braking process

The phase of flight which occurs immediately after touchdown is a phase of braking (landing roll). The aircraft moving with a touchdown speed reduces it to make it possible to turn into the runway exit.

In civil aviation, the aircraft brakes by using the:

- wheel brakes,
- aerodynamic brakes,
- thrust reverses.

Braking with the use of wheel brakes can be done in two ways (FSF, 2009):

- by manual braking, where the braking force is controlled by the pilot who uses the brake pedal; this type of braking is used during emergency situations and on short runways when it is needed to stop the airplane as soon as possible,
- by automatic braking (autobrake), which starts to operate after touchdown when an aircraft’s force pressure on the runway is large enough to make the braking effective; the braking force is determined based on the range selected by the pilot as well as by the aircraft speed.

For aerodynamic braking, the aircraft uses (FSF, 2009):

- aerodynamic brakes; these are usually tilting surfaces on top of the aircraft’s wings which increase the aerodynamic drag without changing the aircraft lift force,
- flaps, which serve mainly to increase the aircraft lift force but at the same time they also increase the aerodynamic drag; they are usually in the extended position after touchdown, thus they increase the efficiency of aerodynamic braking,
- spoilers, whose main task is to decrease the aircraft lift force as soon as possible so that the automatic braking process becomes possible; spoilers also increase the aircraft aerodynamic drag.

The thrust reverser is a device that is used to change the direction of the engine thrust by changing the direction of the exhaust gas stream that is opposite to that of the aircraft movement direction. The thrust reverser allows the aircraft to land on the runway with reduced adhesion (i.e. with a wet or icy surface). It also reduces brake and tire wear.

There are many constructions of thrust reversers. The most common in modern turbofan engine constructions is a solution in which only the external air stream from the engine is reversed (Balicki et al., 2010). This solution is characterized by a

Please cite this article in press as: Skorupski, J., Wierzbicki, H. Airport capacity increase via the use of braking profiles. Transport. Res. Part C (2016), http://dx.doi.org/10.1016/j.trc.2016.05.016
simple construction and does not require the use of materials that are resistant to high temperatures because the external stream has an ambient temperature. Although this type of thrust reverser uses only a part of the exhaust stream, its effective reverse thrust is even 60% of the nominal thrust. Reversing the air flow in such a construction is done by single flaps. These are integrated with the inner part of the engine housing and are symmetrically arranged around its circuit (Huenecke, 1997). Other solutions of thrust reversers were analyzed in a paper by Qian et al. (2011).

The engine’s reversed thrust characteristics depend on true air speed (TAS) and rotational speed of the low-pressure rotor which is the most important from the point of view of an aircraft braking with the thrust reverser. During the landing roll phase, the aircraft braking with the thrust reverser deployed is characterized by the following features:

- the reverse thrust value increases with the increasing engine rotational speed,
- the reverse thrust value decreases with the decreasing TAS,
- the most effective aircraft braking takes place when it moves with a speed that is close to the touchdown speed and the engines are working at maximum rotational speed; during a landing roll the effectiveness of the thrust reverser decreases, which means that at low speeds in the final phase of the roll it is recommended to brake the aircraft with the wheel brakes instead.

1.4. Concept of the study

The literature review shows a lack of studies on standard BPs which take into account the issue of runway capacity. Our study fills this gap. We introduce the following research problem: How should available braking resources be used in order to achieve the maximum runway capacity? By maximum capacity we mean also various additional criteria such as minimization of noise, reduction of tire wear, and maximization of passenger comfort. The results of these analyses are presented in Section 3. In the final part of the paper we also present a wider look at the issue of capacity. It turns out that proper control of the braking process can increase the capacity of the entire airport, even though the runway occupancy time for one of the runways is not minimal. The calculations and results will be presented on the example of Warsaw Chopin Airport (ICAO code: EPWA).

This paper is a continuation of Manerowski et al. (2014). The analysis was extended to take into account the:

- rolling friction in the aircraft movement equations,
- ability to control the braking force of the wheel brakes and thrust reverser (by controlling the rotation speed of the low-pressure rotor),
- new criteria for evaluating BPs,
- runway’s layout in the analysis of airport capacity.

A simulator, the ACPENSIM (Airport Capacity Petri Net Simulator), was developed to find the best braking profile. It allows us to create more accurate BPs which consist of many phases.

The remaining part of this paper has the following structure. Section 2 discusses the model of the braking process that is used and the possibility of using Petri nets for modeling this process together with the ACPENSIM simulator which was created for this purpose. A typical BP and a short discussion regarding safety issues in braking on the runway process are also presented. Section 3 contains the results of the studies whose aim is to create the recommended BPs with different evaluation criteria: minimizing the runway occupancy time, minimizing the noise, tire wear or maximizing passenger comfort. In Section 4 a wider view of the problem is presented. We suggest BPs which fulfill, to a large degree, all of the criteria as referred to above and which also seek to maximize the capacity of the whole airport, not only a single runway. In Section 5 a summary, final conclusions and further work plans are presented.

2. Braking process model

The main purpose of this paper is to show the possibility of supporting the efficient use of available braking resources during the aircraft landing roll. The landing process model which was used is relatively simple but reliable. This was intended because the simulator is based on a numerical prediction of further aircraft movement, which should be performed in real time. With the excessive complexity of the mathematical model, one may find that the time required for the calculation is too large, which would put the concept into question. However, the measurements that were carried out initially confirm the model’s adequacy.
the area of analysis is the aircraft landing roll, beginning from the touchdown point and ending at the point where the aircraft turns into a taxiway, usually via a rapid-exit taxiway,

- the location of the touchdown point on the runway and the touchdown speed are available input data; they may be different for each landing, but actual realization of this random variable must be known,

- the designated runway exit is determined in advance, for example by the air traffic controller,

- the final speed of the landing roll is the input variable; this speed may depend on the exit taxiway configuration,

- other available data are: aircraft lifting surface, aircraft weight and the wheels' braking drag coefficient, which depends on the runway surface condition,

- the optimization criterion is one of the following: minimization of ROT, noise, tire wear or maximization of passenger comfort,

- the output variables (decision variables) are: the moments in time when the aircraft begins and ends braking with the use of the thrust reverser and with wheel brakes; moreover, the rotation speed of the low-pressure rotor, which unambiguously defines the thrust reverser braking power as well as the wheels' braking power.

In the model, the time was adopted as a discrete value and the discretization step $\Delta t$ was adopted to be equal to 0.1 s. During the landing roll the aircraft moves by decelerated movement (Dommasch et al., 1961). The forces affecting an aircraft during the landing roll are presented schematically in Fig. 1.

$$m \frac{\Delta V}{\Delta t} = P_i + P_x + H + T_p + W$$  \hspace{1cm} (2)

where

- $m$ – mass of the landing aircraft,
- $V$ – aircraft speed,
- $P_i$ – reversed thrust at time $t_i$ produced by the engine with the thrust reverser deployed (obtained from CFM (2005)),
- $P_x$ – aircraft drag force at time $t_i$,
- $H$ – wheel braking force,
- $T_p$ – rolling friction force which occurs during the landing roll,
- $W$ – wind force component which causes an additional increase or decrease of the braking force depending on which side the wind blows.

By transforming the formula (2), we obtain

$$\frac{V_i - V_{i-1}}{\Delta t} = \frac{P_i + P_x + H + T_p + W}{m}$$  \hspace{1cm} (3)

and then the formula for instantaneous speed

$$V_i = \frac{\Delta t}{m} \left( P_i + P_x + H + T_p + W \right) + V_{i-1}$$  \hspace{1cm} (4)

We take into account the fact that the aerodynamic drag force at time $t_i$ is equal to (Eurocontrol, 2012)

$$P_x = C_x \cdot S \cdot \frac{\rho \cdot (V_{i-1})^2}{2}$$  \hspace{1cm} (5)

where

- $C_x$ – drag coefficient determined for the lift force coefficient $C_z = 0$,
- $S$ – aircraft lifting surface,
- $\rho$ – mass density of air.

The wheel braking force is given by (Dommasch et al., 1961)

$$H = \mu_d \cdot m \cdot g \cdot k$$  \hspace{1cm} (6)

![Fig. 1. The forces affecting an aircraft during the landing roll.](image)
where 
\[ \mu_p - \text{drag coefficient during braking with the use of wheel brakes,} \]
\[ g - \text{gravitational acceleration,} \]
\[ k - \text{coefficient that shows the use of the wheel braking force, related to the force used for pressing on the brake pedal,} \]
\[ k \epsilon [0, 1]. \]

The rolling friction drag can be described by the formula (Brandt et al., 2004)
\[ T_p = \mu_p \cdot m \cdot g \]  
where \[ \mu_p - \text{coefficient of rolling friction.} \]

Finally, the formula for aircraft speed at time \( t_i \) is
\[ V_i = \frac{\Delta t}{m} \left( P_i + C_x \cdot S \cdot \frac{\rho \cdot (V_{i-1})^2}{2} + \mu_d \cdot m \cdot g \cdot k + T_p + W \right) + V_{i-1} \]  

We denote the moment in time when the plane reaches the set speed \( V_k \) by \( t_k \). Then the length of the landing roll is equal to
\[ L = \sum_{i=0}^{k} l_i = \sum_{i=0}^{k} V_i \cdot \Delta t \]  
and the landing roll time
\[ T = \sum_{i=0}^{k} \Delta t \]

The calculation tool (ACPENSIM simulator) was created by using the presented mathematical model. The tool allows to estimate the landing roll distance, runway occupancy time (ROT) and deceleration affecting the passenger. The simulator is described in more detail in Section 2.3.

In further calculations it was assumed that the thrust reverser activation time is negligible and the touchdown point is known. The main purpose of the method, and the concept of its further use, is to aid one specific landing. In such a case, the touchdown occurs at a specific point, which of course cannot be predicted earlier. The simulator allows one to determine the braking profile for any random touchdown point. During calculations presented below it was assumed that the touchdown point is constant (see Fig. 12), but only for the comparability of the results for different optimization criteria and braking profiles. The analysis is performed for a Boeing 737-300 aircraft. The following input data were used (Brady, 2014; March, 2008; Raymer, 1992; Torenbeek, 1982; Schaufele, 2000):
\[ V_0 = 278 \text{ km/h (150 knots),} \]
\[ C_x = 0.16, \]
\[ S = 105.44 \text{ m}^2, \]
\[ m = 45,000 \text{ kg,} \]
\[ l_d = 0.4, \]
\[ l_p = 0.02, \]
\[ q = 1.168 \text{ kg/m}^3, \]
\[ g = 9.81 \text{ m/s}^2, \]
\[ W = 0. \]

It was assumed that the aircraft is equipped with two CFM56-3 turbofan engines. Their reversed thrust \( P_i \) related to the rotational speed of the low-pressure rotor with the thrust reverser enabled can be found in (CFM, 2005).

The calculations of the braking time and distance for any braking scenario will be performed by simulation using the discrete simulation technique. On the basis of classical mechanics it is of course possible to obtain a formula which allows for computation of the moment in time when the braking process has to begin when the braking distance is given. However, the practical possibility of using analytical approach is limited. Braking distance can be determined accurately only when input data are available, credible and accurate. However, many parameters are in fact uncertain, may be subject to some error or even may vary during a single landing. It should be noted that the following phenomena (interference) can occur in practice:

- each of the devices used to brake (thrust reverser and wheel brakes) can be deployed or stowed at any time,
- while braking with the use of the thrust reverser, several different rotational speed values of the low-pressure rotor can be used; additionally, they may be changed during the braking process,
- while braking with the wheel brakes, the force used to press the brake pedal may change,
- the friction coefficient value is not exactly known; in practice it is measured with specific vehicles but it can change fast or it may be different in different parts of the runway,
- the wind force and direction, aircraft weight and air density are not exactly known.

The parameters of the environment as listed above are possible to measure, but in practice they are not known exactly or they change very often, and thus during a single landing they may differ from the predicted values. This justifies the adoption of simulation method and was reflected in the concept of the whole system. Instead of treating such data by methods appropriate to the uncertainty (e.g., using probability or fuzzy theory), the idea is to repeat calculations of the braking profile in real time, wherein each successive calculation is performed taking into account new information about the traffic parameters.
The discrete model of the braking process implemented using a colored Petri net was used in this paper. The use of Petri nets is justified, because the ACPENSIM simulator is a part of the future Brake Assistance System, in which many parameters, which are now fixed, will be determined simultaneously with simulator. This applies to determining the actual touchdown point, deviations from the planned traffic parameters resulting from the wind, variable friction coefficient, etc. They are outputs from various processes which run concurrently with the braking process. Hence an adequate modeling mechanism is necessary. Petri nets provide a convenient tool for modeling dynamic concurrent systems.

2.2. Petri net for braking process simulation

Petri nets (Jensen, 1997; Marsan et al., 1999; Reisig, 2013) can be an excellent tool for simulation analysis of BPs during the landing roll. Originally, they were developed for modeling computer systems working synchronously. However, their high versatility has resulted in their having many other applications in recent years, including modeling and support of air traffic management processes (Werther et al., 2007; Oberheid and Söffker, 2008; Skorupski, 2011, 2015; Davidrajuh and Lin, 2011).

In this paper, a hierarchical Petri net was implemented. Its essence is decomposition of a model for multiple subnets (pages) that are combined through “substitution transitions” and “fused places”. These indicate nodes that simultaneously belong to several sub-models, thereby connecting them and allowing to transfer tokens between subpages.

2.3. Braking process simulator – ACPENSIM

The braking process simulator supporting management of the runway capacity was developed using the CPN Tools 4.0 software package. This is an advanced and increasingly popular package for creating models in the form of Petri nets, in their simulation and analysis in state space. In this section, the basic idea of this simulator will briefly be presented.

The ACPENSIM simulator consists of three subpages:

- **Main** – the home page. It models the aircraft’s movement from touchdown to the beginning of braking. It contains current movement parameters (speed, acceleration) and takes into consideration the system time flow. Additionally, it stores information about the movement parameters in consecutive time moments – the braking profile.
- **Check roll** – this page determines the distance that is necessary to achieve the appropriate speed to exit the runway if the plane was moving without using wheel brakes and the thrust reverser.
- **Braking** – the page that models three phases of aircraft braking. In each phase it is possible to determine the thrust reverser and the wheel brakes’ braking force.

The place **Start** on the page **Main** (Fig. 2) allows to determine the distance that the modeled aircraft has to move. It is given by the planned runway exit taxiway, and in the presented example it is equal to 2010 m. The transition **Touchdown** is respon-
sible for operations related to aircraft touchdown. In particular, the weight of the arc connecting transition Touchdown with the place Roll determines the time that the plane moves with aerodynamic braking only. In our example this is 30 sec. The place Roll is used to connect pages in the hierarchy and is generally responsible for counting the time remaining until the end of the current phase of the landing roll. In turn, the place Time is responsible for the system time flow. The transition Move synchronizes the calculation of the movement parameters along with the time flow (places Position and Parameters).

The transition Stop braking is responsible for actions that are taken at the time when the aircraft reaches such motion parameters that will enable it to reach the speed that is appropriate to turn into the desired taxiway without braking. The place Profile is responsible for storing the BP data. Fig. 2 also shows references to functions aero, rvt, brk, and rdg which define the parameters of braking, respectively, aerodynamically, with the thrust reverser, wheel brakes and by rolling drag. These functions are consistent with the model described in Section 2.1; their software code is not presented.

The subpage Check roll (Fig. 3) represents a simulation model of the aircraft’s movement in the case when only aerodynamic braking takes place. Its main tasks include determining the speed during motion (place Roll speed) and comparing it to the preset target speed (transition Stop roll). If these are equal, then the distance necessary to achieve the desired speed is determined and returned to the Main page through the place Distance to Stop.

Fig. 4 presents the subpage Braking of the ACPENSIM simulator. It is responsible for mapping the three phases of braking which correspond with transitions Braking 1, Braking 2, and Braking 3. The weights of the arcs determine the times of the phases and aircraft parameters; for instance, the arc connecting the transition Braking 2 with place Roll 1 (in the example
the weight is equal to 10.0) indicates that the second braking phase will last 10 s. In turn, the parameters of this braking phase are determined by the weight of the arc connecting the transition Braking 2 with the place Parameters. This place is synonymous with the place of the same name on the subpage Main. In the example, this phase involves simultaneous braking with the reverser (rotational speed equal to 60% of the maximum) and with wheel brakes (pressure on the brake pedal equal to 40% of the maximum strength). Places B1, B2 and B3 are responsible for controlling the change of the braking phase.

2.4. Typical braking profile used in practice

A typical braking procedure (B0) begins just after aircraft touchdown with an almost maximal braking force both with the use of wheel brakes and the thrust reverser. Then, after substantial speed reduction, the aircraft rolls freely, braking only by aerodynamic drag and rolling friction drag. If the aircraft decelerates too much, it is also possible to use additional thrust to maintain or increase the current speed. This procedure is very good from the safety point of view, but, as we shall show further, it results in a very large runway occupancy time. The simulation of the results of this kind of BP allows us to find the upper bound of the ROT for the searched solution.

Fig. 5 shows the characteristics of aircraft speed and distance as a function of time, assuming that the aircraft brakes using the braking profile B0 described above. It was also assumed that the runway exit is located at a distance of 2010 m from the touchdown point (accordingly to the use of exit S from runway 33 at Warsaw Chopin Airport (Fig. 12)), and that the maximum speed at this point equals 17 m/s.

As one can see that the total ROT while using this BP B0 is about 70 s. It consists of 6.2 s of braking with the thrust reverser and the wheel brakes with maximum force. During this time the aircraft moves only by 358 m, whereas the speed is reduced to 38.9 m/s. For the remaining 1652 m the plane rolls freely. The influence of aerodynamic drag and rolling friction results in further braking until the aircraft reaches a speed below 17 m/s at the beginning of the target exit taxiway.

3. Determination of the standard braking profile at different optimization criteria by simulation

The mathematical model of the braking process and simulation tool based on colored Petri nets allows to determine the braking profile (BP) that meets the control objectives. As will be shown in subsequent sections, these objectives may be different.
3.1. Minimization of the runway occupancy time

The braking procedure $B_s$, resulting in the shortest ROT, is somewhat inverse to the typical profile that is used in practice. It involves covering some distance without braking, and then braking with maximum force of the thrust reversers and wheel brakes. This procedure gives the smallest runway occupancy time but carries the risk that the aircraft will pass by the designated exit taxiway (in case of any disturbance in the braking process) or, in the extreme case, the risk of an accident of the runway excursion type. The result obtained for strategy $B_s$ allows to determine the lower bound of the ROT for the searched solution. Braking profile described in Section 2.4 is characterized by a very low passenger comfort. At the moment of deploying the thrust reverser and wheel brakes, the deceleration is about $7 \text{ m/s}^2$. In the profile $B_s$ which minimizes the ROT the passenger comfort is much higher.

Fig. 6 shows the characteristics of the aircraft speed and distance as a function of time at maximum braking but deployed after moving the distance calculated to achieve the appropriate speed exactly when reaching the exit taxiway.

As can be seen, BP $B_s$ provides significant shortening of the ROT, i.e. from ca. 70 s to ca. 38 s. Thus it is the most preferred BP from the runway capacity point of view. Its application in practice is possible but would require very detailed knowledge of all parameters affecting the braking distance, e.g. the state of the runway. It would be necessary therefore to use a certain safety buffer to increase the likelihood that the aircraft would be able to slow down to the appropriate speed in the vicinity of the target exit taxiway.

3.2. Minimization of brake system wear

Braking with the intensive use of wheel brakes entails some costs to the air carrier. These result from the rapid wear of tires and mechanisms comprising the braking system of the aircraft. These costs are not only material costs but also maintenance costs associated with replacement of aircraft tires and the entire brake mechanisms, and also costs associated with unavailability of the aircraft during maintenance. As soon as the tires wear out faster, in the remaining part of this section we will refer only to this parameter.

If we take minimization of tire wear as one of the optimization criteria, then two cases are possible. The first occurs when the use of wheel brakes is not necessary at all. An example of such a BP (designated $B_t$) is shown in Fig. 7.

Saving the tires was the main criterion considered here, but the secondary criterion was to reduce the ROT. As can be seen in Fig. 7, the ROT is larger than in BP $B_s$, minimizing the ROT, and smaller than in the basic profile $B_0$. This is obviously not the only BP that meets the requirement to minimize tire wear by not using wheel brakes. Also, it is not the BP that gives the minimum ROT under this constraint. The simulation (not presented in the paper, except for the result) shows that it can be obtained if the thrust reverser is deployed after rolling for 1038 m from touchdown. It is then possible to obtain ROT that
is equal to 43.2 s, which is very close to the minimum of 37.6 s. However, this kind of BP is difficult to recommend for general use because it requires to brake with the thrust reverser at very low speeds when its efficiency is low.

The second case which may occur with such an optimization criterion is when the slowdown to the assumed runway exit is impossible without using wheel brakes. The wheel brakes should then be activated as late as possible, at the lowest possible speed. Fig. 8 shows the BP \( B_{t2} \) analogous to the one presented in Fig. 7 \( (B_{t1}) \), but with the target runway exit located at a distance of 1124 m from the touchdown point. In addition, calculations were carried out for scenario when the runway is covered with a mixture of water and snow, as in the case of sleet. For such conditions it can be estimated that the friction coefficient has a value of \( \mu_d = 0.12 \) (Raymer, 1992). Also, at such braking conditions the wheel brakes are less effective and therefore a BP in which the brakes are used to a small extent is even more justified.

As can be seen, the use of wheel brakes is necessary in order for the aircraft to slow down on a short distance. Simulation analysis shows that the brakes need to be deployed after moving 694 m, during which the aircraft brakes only with the thrust reverser and aerodynamically. The total braking time in this case is nearly 25 s, and the time of using the wheel brakes – ca. 13 s. If the brakes are to be used longer but not with full force, then the most preferred option seems to be BP \( B_{t3} \), which consists in using both the reverser at 90% of the maximum and the wheel brakes at 50% of the maximum throughout the whole landing roll (Fig. 9). This extends the total ROT to 27.4 s.

3.3. Minimization of noise

The braking strategies that are presented in Section 3.2 are based on maximum use of the thrust reverser braking force. This gives a reduction in costs resulting from tire wear, but it does have some drawbacks. Braking by thrust reversers causes emission of a large amount of noise. At many airports, environmental (noise) constraints preclude such procedures. This applies mainly to the night period, when it is prohibited to exceed certain levels of noise. However, restrictions on the total emission of noise may also apply at other times of the day.

Accordingly, three braking strategies that reduce the level of noise were analyzed. The first of them, \( B_{n1} \), does not provide for the use of a thrust reverser, but only of braking by using wheel brakes. The second, \( B_{n2} \), involves the need for the reverser. Such a situation occurs when, for example, the runway is covered by a mixture of water and snow; then it is necessary to take into account the reduced friction coefficient \( (\mu_d = 0.12) \). In this BP we propose to use the smallest possible reverse thrust. The third strategy, \( B_{n3} \), consists in very short use of the thrust reverser. The results are presented in Fig. 10. Use of the exit taxiway located 1124 m from the touchdown point was assumed.

Braking which takes place in good weather conditions and on a dry runway has the lowest ROT \( (B_{n1}, \text{Fig. 10a}) \). There is also no need to use the thrust reverser. In the case of a landing roll performed on a runway covered with a mixture of snow and water, the use of a thrust reverser is necessary in order to slow down the aircraft enough to use the planned exit from the
runway. In order to minimize the level of noise, the thrust reverser should be used for the shortest time possible. Such a BP (designated as $B_{n3}$) is illustrated in Fig. 10c. By using the $B_{n3}$ profile, we may obtain ROT of about 24 s, and the use of the thrust reverser time is approximately 14 s. Another approach consists in reducing the noise level at the expense of the length of its duration. BP $B_{n2}$ corresponding to this approach is presented in Fig. 10b. In this case we are dealing with longer ROT and a longer time period to use the thrust reverser; but in this case it is required to use only 50% of the reverse thrust instead of 90%, as was in the previous case.

### 3.4. Maximization of passenger comfort

All of the previously presented BPs assumed that the braking equipment (reverser, brakes) may be used with high intensity. Such action results in the existence of large gradients of deceleration, which is uncomfortable for passengers. In this section we present a simulation determination of BP (designated as $B_{c}$) in which the basic criterion is passenger comfort. This will be achieved through such use of the braking devices that deceleration will be less than 2 m/s$^2$. Fig. 11 shows an exemplary BP that meets these constraints. Use of the exit taxiway located 2010 m from the touchdown point was assumed (Fig. 12).

The details of this BP are as follows:

- for 15 s the plane uses neither the thrust reverser nor wheel brakes; it brakes aerodynamically,
- after 15 s the thrust reverser is deployed, the rotational speed is equal to 70% of the maximum,
- after the following 10 s the thrust reverser is stowed while the wheel brakes are activated, the braking force is only 30% of the maximum,
- after 41 s the brakes are disabled.

As can be seen, the ROT of profile $B_c$ differs only slightly from profile $B_s$, which maximizes the runway capacity. However, in the case of landing during lower traffic, when minimizing ROT is not that important, this way of braking should be considered because the passengers’ negative perception is relatively small for this BP.

### 3.5. Braking process safety

An important aspect to be considered when proposing a solution to the problem of reasonable BP is the issue of safety. It should be noted that under no circumstances should an attempt to increase runway capacity by minimizing runway occu-
pancy time increase the risk of a runway excursion accident due to having the braking distance exceed the LDA (landing distance available). In case any problems may arise, for instance, due to the state of the runway surface, wind or other threats, it is necessary to leave any calculated BP and to begin emergency braking with maximum use of all available means. On the other hand, the discussed model and the proposed support system may have a very positive impact on safety, in addition to the positive impact on bandwidth. It happens that, for various reasons, the plane does not leave the runway by a predetermined exit taxiway and thus the plane that is next in the landing queue cannot perform the landing procedure and must go

![Graph](image1)

**Fig. 9.** Braking profile $B_{t3}$ minimizing tire wear, when the use of wheel brakes is necessary.

![Graph](image2)

**Fig. 10.** Braking profile minimizing the level of noise during landing; (a) $B_{n1}$ – the case of braking without the use of a thrust reverser, (b) $B_{n2}$ – the case of braking at the smallest reverse thrust, with a reduced friction coefficient and (c) $B_{n3}$ – the case of very short use of the thrust reverser, with a reduced friction coefficient.
around. This is an unusual event which may cause traffic problems and therefore reduce the level of safety. Use of the proposed system for selection of BP should decrease the likelihood of such occurrences and thereby should increase the safety of air traffic.

4. Example of model utilization – determining the standard BP for Warsaw Chopin Airport

The essence of the proposed model and support system in the context of airport capacity is to find a BP which reduces ROT. We will show that for a real case (Warsaw Chopin Airport) we can use the method to affect the ROT, thereby affecting the runway capacity. And when the ROT is not the critical parameter, we can take into account other criteria during BP assessment.

We will analyze landing on runway RWY 33, which is the most frequently used runway for this operation (Fig. 12). We assume that there are four possible target exit taxiways for landing on this runway: J/T – at a distance of 1124 m from the touchdown point, S/O1 – 2010 m, R1/D2 – 2676 m, and A0 – 3276 m from the touchdown point. When leaving the runway via exits J, S and R1, the aircraft can have a speed of 17 m/s. However, leaving runway RWY 33 via one of the T, O1, D2, and A0 exit taxiways requires speed reduction to 5 m/s.

4.1. Selection of a BP as a compromise when using different evaluation criteria

By using formulas (2)–(10) and the developed computer simulation tool, it is possible to compare the effectiveness of different BPs. As shown in Section 3, there are various criteria for selecting the reference BP and, in fact, a multi-criteria analysis should be performed (Skorupski, 2014). But this goes beyond the scope of this work. We will present heuristic BPs which largely meet all of these criteria. Their general characteristics are as follows:

- after touchdown the aircraft moves without braking for some time; deceleration takes place due to aerodynamic drag and rolling friction drag,
- then thrust reverser braking is applied with the low-pressure rotor at moderate rotational speed (60-70% of the maximum),
- applying the wheel brakes follows with medium intensity (60-70% of the maximum); at the same time the thrust reverser is stowed,
- then the wheel brakes are disengaged and the plane rolls to the exit of the runway; this piece of the BP aims to create a safety buffer that can be applied if the actual braking parameters are worse than anticipated.

![Braking profile](image)

Fig. 11. Braking profile $\beta$, which is comfortable to the passenger (deceleration less than 2 m/s$^2$).

Please cite this article in press as: Skorupski, J., Wierzbicki, H. Airport capacity increase via the use of braking profiles. Transport. Res. Part C (2016), http://dx.doi.org/10.1016/j.trc.2016.05.016
Examples of the braking process parameters and the durations of individual phases during the landing roll for so-called high speed exit taxiways are presented in Table 1. These are consistent with the BP as described above. It is a compromise in the sense that it seeks to simultaneously provide low ROT, low tire wear, low noise and high passenger comfort. It is obvious that these criteria are contradictory, therefore, presented BPs meet them only to a certain extent. However, they can be considered acceptable. Table 1 shows three different profiles based on the same assumptions, each for a different runway exit. ROT is given in Table 1 just for information, it was not a criterion for optimization.

An examination of the deceleration profiles shows that for all exits from runway RWY 33, it is possible for a Boeing 737-300 aircraft to finish the landing roll safely and to use them with at least partial fulfillment of all criteria for the evaluation of the BP. Because presented criteria are partly contradictory, this approach is partially subjective. It is therefore important in future attempts to try to establish some objective rules of defining compromise BPs.

4.2. BP maximizing the airport capacity

In the preceding discussion related to the capacity, we tried to find a BP that would minimized the ROT. In this section we will show that our model also allows for a broader look at the issues discussed here.

Warsaw Chopin Airport has two intersecting runways arranged as in Fig. 12. The terminal’s configuration and traffic conditions result in the fact that the following operating procedure is applied most frequently: take-offs take place from runway RWY 29, landings are on runway RWY 33 (as analyzed in the previous sections). In the case of mixed traffic (i.e. with a similar number of takeoffs and landings taking place), the basic traffic parameter determining the capacity of the entire airport is the time necessary for the aircraft to pass the runways’ intersection. In the case of a plane landing on runway 33, passing the intersection is a prerequisite to begin take-off from runway 29. Similarly, passing the intersection by an aircraft that is taking off allows to begin landing on runway 33.

In such a situation the following question arises: is it truly so important to minimize the ROT by a landing aircraft? Perhaps it is more important for the landing aircraft to move as quickly as possible in order to pass the intersection, even at the expense of occupying runway 33 longer, e.g. due to the need to use exit taxiway R1 instead of S.

Table 1
Traffic parameters for BPs for different speed exits from RWY 33.

<table>
<thead>
<tr>
<th>Reverser and wheel brakes’ braking force (%, %)</th>
<th>Duration of the phase (s)</th>
<th>ROT for exit taxiway J</th>
<th>Reverser and wheel brakes’ braking force (%, %)</th>
<th>Duration of the phase (s)</th>
<th>ROT for exit taxiway S</th>
<th>Reverser and wheel brakes’ braking force (%, %)</th>
<th>Duration of the phase (s)</th>
<th>ROT for exit taxiway R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td>23.8</td>
<td>0.0</td>
<td>17</td>
<td>43.0</td>
<td>0.0</td>
<td>36</td>
<td>57.1</td>
</tr>
<tr>
<td>70.0</td>
<td>11</td>
<td>70.0</td>
<td>11</td>
<td>11</td>
<td>70.0</td>
<td>11</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>0.70</td>
<td>11</td>
<td>0.60</td>
<td>8</td>
<td>0.60</td>
<td>4</td>
<td>0.60</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>0.0</td>
<td>2</td>
<td>0.0</td>
<td>7</td>
<td>0.0</td>
<td>5</td>
<td>0.0</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

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Fig. 13 shows the results of calculations for BP which do not reduce the ROT much but rather minimize the time of movement from the runway 33 threshold to the intersection of runways. It was assumed that the aircraft leaves the runway via the R1 exit. With the parameters used in the present example, it is also possible to leave the runway by using the most often used exit taxiway S, but this requires maximum braking by all means just after passing the intersection of runways. This solution results in considerable wear of the braking system components and is not very comfortable for the passengers, so it will not be considered here.

The details of this BP are as follows:

- for 30 s the plane uses neither the thrust reverser nor the wheel brakes, which allows for fast movement from touchdown to the runways' intersection; the time to reach the intersection is 28 s,
- after 30 s the thrust reverser is deployed, the rotational speed is equal to 60% of the maximum,
- after the following 5 s the thrust reverser is stowed and the aircraft rolls, braking only aerodynamically,
- after 45 s from touchdown the wheel brakes are activated, the braking force is equal to 40% of the maximum,
- after the following 10 s the brakes are disabled.

As was stated before, this BP results in having the landing aircraft reach the runways' intersection in 28 s. Then the next aircraft waiting on RWY 29 may begin takeoff. As can be seen, it is possible to perform another operation after a time period that is much smaller than 43 s of the ROT as defined in Table 1 for the most often used exit taxiway S. Of course, the value of 28 s should be compared with the time of occupying the segment from touchdown to the intersection of runways for the BP from Table 1. The benefit is relatively small because it amounts to about 2 s, but this results from the distinct and unfavorable distribution of exit taxiways at Warsaw Chopin Airport. For other locations of exit taxiways or other touchdown points, the differences may be much greater.

5. Summary, final conclusions and further work

The mathematical model and the computer calculation tool based on colored Petri nets (ACPENSIM simulator) allow to determine the BP using the thrust reverser and the wheel brakes, which allows for optimization of the ROT or another criterion (minimization of noise, minimization of tire wear, maximization of passenger comfort). It is also possible to find solutions combining several criteria.

In the paper we showed the possibility of effective control of the braking process so as to obtain the expected operational results. Among them, an increase of the runway capacity seems to be the most important, and therefore an increase of the

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entire airport capacity. However, in certain situations the following criteria may be equally important: noise or tire wear minimization or passenger comfort maximization. The results show that the typically used BP is disadvantageous from the throughput point of view. In the example shown here (runway 33, exit taxiway S), this BP gives ROT of about 70 s, while the minimum attainable one is 38 s. Solutions that take into account other criteria have ROT falling somewhere between these values; for example, by maximizing passenger comfort (defined as not exceeding deceleration of 2 m/s²), we can obtain ROT of 42 s. In turn, when minimizing tire wear, ROT equals to 50 s. Interesting are also the results showing that in the case of two intersecting runways (as is the case at Warsaw Chopin Airport), it may be preferable to elongate the ROT for a single runway by selecting the exit taxiway located farther along the runway. This allows to find a BP which gives the shortest time to reach the runways' intersection, which is very favorable in the case of traffic involving takeoffs from one runway and landings on the other.

An important aspect that requires discussion is the safety of the proposed solutions. It may be questioned whether a landing roll with braking starting after some time is safe and whether there is a risk of a runway excursion accident. Undoubtedly, the probability of this happening is greater if braking does not start immediately. However, it is worth noting that this approach is sanctioned formally and practically. Indeed, a commonly used procedure is to displace the runway threshold (Horonjeff et al., 2010; FAA, 2011). This means that a runway threshold is located at a point away from the physical beginning of the runway. This shortens the available runway length but increases any obstacle clearance and reduces the noise below the approaching aircraft. In this solution aircraft touches down farther, so the probability of an accident of the runway excursion type is greater. In the solution proposed in this paper, the practical effect is similar to the displaced runway threshold, but it is much safer. In case of any abnormalities, it is possible to modify the BP through immediate rapid deceleration by all means.

The model itself and the results achieved can be the basis for creation of a decision support system for the pilots, who will also be of benefit for aerodrome traffic management. The target solution is a system that automatically, continuously and smoothly chooses the rotational speed of the low-pressure rotor and the strength of wheel brakes’ application. Such a system is currently under development.

The mathematical model used in our solution is relatively simple. However, we do not consider this as a disadvantage. In the practical application, many random disturbances will occur which cannot be predicted. The automatic system of BP selection needs input parameters to be determined dynamically, depending on factors such as aircraft configuration, amount of fuel in the tank, meteorological conditions and runway conditions. On that basis the system will, in each step of the operation, compare real traffic parameters (aircraft position and speed) with those defined in the nominal BP. In the case of any differences it will calculate a new BP. Significant detailing of the mathematical model is not advisable in this case due to the limitation of time that is available for the real-time calculations and due to inability to take into account a number of random disturbances.

References


