Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2012, Article ID 518493, 9 pages
doi:10.1155/2012/518493

Research Article

Analysis of the Effect of the Length of Stop-Spacing on the Transport Efficiency of a Typically Formed Conventional Locomotive Hauled Passenger Train in China

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Received 7 May 2012; Accepted 26 September 2012

Academic Editor: Huimin Niu

By utilizing a computer-aided simulation approach, this research analyzes the detailed effect of the length of stop-spacing on the transport time per passenger-kilometer of a typically formed Chinese intercity passenger train hauled by, respectively, representative types of the locomotives utilized in China for different target speeds. It is empirically confirmed that a stop-spacing longer than approximately 20.00 km has little influence upon the transport efficiency of the train. In contrast, shortening the stop-spacing below about 20.00 km increases the transport time per passenger-kilometer of the train evidently, in particular for a target speed much higher than some 40.00 km/h. Therefore, the target speed of such a train providing transport service on a railway line whose transport capacity has not been much consumed ought to be changeable according to the length of each stop-spacing rather than consistent for the whole trip.

1. Introduction

Although the high-speed railway trains in China are playing more and more important roles in the work of intercity passenger transports, the Conventional Locomotive Hauled Passenger (CLHP) trains are still popularly preferred today by most of Chinese people for their intercity trips. According to the statistic data released by the Ministry of Railways of the People's Republic of China, around 80.00% of more than 1.67 billion [1] passenger trips undertaken in China by railway trains in 2010 have been completed by the CLHP trains. Besides the advantages of punctuality, low fares, and so forth, the relative rapidity of the CLHP trains is also essential to have them favored for intercity trips in China.

It is commonly believed that a high target speed which a train strives to reach in its transport process between neighboring stops makes the train run fast and therefore transport passengers or freight efficiently. However, many other factors including the ramps, bends, and so forth of the rail line [2–5], the traction performance (such as the full traction power) of the train [6–8], the weights of different railway cars forming the train [9, 10], and the length of the stop-spacing [2, 11–14] all have strong influence upon the average speed of the train especially with a high target speed and accordingly its transport time per passenger-kilometer, that is, the transport efficiency. Many researchers and practitioners have been making continuous effort to interpret the relationship between the target speed of a train and its transport efficiency in consideration of various elements [15–17]. Nevertheless, the exact impact of the transport distance between neighboring stops on the time consumed per passenger-kilometer of a transport mission completed by a CLHP train for its different target speeds in view of other factors, for example, the traction performance of the applied locomotive, and so forth, still needs to be further explored in detail.

Based on the computer-aided simulations of the passenger transports by a typically formed Chinese CLHP train with different target speeds on a railway line with various distances between neighboring stops, this study attempts to clarify the quantificational effect of the length of stop-spacing on the passenger transport efficiency in an accurate manner. Additional regards are also paid to traction performances of various types of the applied locomotives of the studied CLHP train. Due to the inadequate support of the data of the alignments of actual railway lines, a hypothetical railway line which is straight and smooth is utilized for this research and the transport efficiencies of the studied CLHP train with a certain target speed and the same utilization ratio of its passenger carrying capacity for different lengths of all the stop-spacings of this railway line are analyzed in comparison. Moreover, because of the little influence of the weight of passengers together with their baggage upon the transport time of a train and usually high travel demands of the passengers of the CLHP trains in China, the utilization ratio of the seats and berths of the studied CLHP train for each stop-spacing is assumed to be the same here as 100.00%.

The latter parts of this paper are organized as follows. The studied CLHP train hauled, respectively, by different types of locomotives and the computer-aided simulation approach applied to compute the Passenger Transport Time (PTT) of the train are explained in Section 2. Next, Section 3 analyzes the detailed changes of the PTTs per 10,000 passenger-kilometers (p-km) of the train with the increase of its target speed for different transport distances between neighboring stops. Finally, Section 4 draws conclusions, makes some suggestions for the passenger transport work of the CLHP trains in China, and points out some future research issues.

2. The Studied CLHP Train and the Simulation Approach

As shown in Figure 1, the Locomotive (Lo) of the studied typically formed Chinese CLHP train in this research hauls 18 railway cars which are in sequence 1 car equipped with the Power (P) unit, 5 cars equipped with passenger Seats (S), 1 car providing Dining (D) services, 1 car equipped with Soft Berths (SB), 9 cars equipped with common Berths (B) and 1 car carrying checked Luggage (L) of the passengers. The type of the cars composing the studied CLHP train is 25 K which is one of the major types of the cars of the Chinese CLHP trains now.

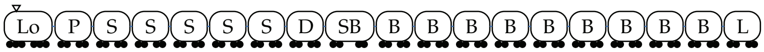

Figure 1: Formation of the studied CLHP train.

The weights of the cars of 25 K for various purposes are, respectively, 60.50 tons (P), 48.80 tons (S), 48.00 tons (D), 66.00 tons (SB), 46.50 tons (B), and 42.40 tons (L) [18]. Therefore, the total weight of the 18 cars forming the studied CLHP train is 879.40 tons. A car of 25 K has 118 passenger seats (S), 36 soft berths (SB), or 66 common berths (B). As a result, the number of the total passenger seats and berths of this CLHP train is 1,220. Because the average weight of a railway passenger together with his/her hand baggage is 80.00 kg [19], the weight of all the passengers together with their baggage in the studied CLHP train is 97.60 tons if all the passenger seats and berths of the train are 100% utilized in the whole process of its passenger transport. This train is, respectively, hauled by two major types of the locomotives for the railway passenger transport work in China, that is, the SS3 and the SS8 which are all electric locomotives. The weights of the SS3 and the SS8 are correspondingly 138.00 tons and 88.00 tons [8]. Their designed top speeds are 100.00 km/h and 170.00 km/h, respectively [8].

By referring to the work of Mao et al. [7], the computer-aided simulation approach presented in Figure 2 is applied in this research to calculate the PTT of the studied CLHP train. The whole transport process of the train from one stop to the next is simulated for one calculation interval after another. The lengths of all the calculation intervals are set to be equal to 1.00 second (s) in this work. Only the traction force and operating condition (i.e., coasting, being in traction or braking) of the train are considered as unchanged values in one calculation interval. The train at a station is started up with its full traction power towards the target speed. With the first achievement of the target speed by the continuous acceleration of the train from its startup, the train commences to be coasted till the difference between its speed and the target speed reaches a predefined constant value and thereafter accelerated in its full traction power to the target speed alternately. In order to ensure the stop of the train in safety in the next station, the train begins to check whether brakes are necessary or not in a calculation interval when it arrives at a rail site where there is a certain distance away from the next stop. This is determined according to the speed ($v1$) of the train and the permitted speed ($v2$) which is decided based on the braking performance of the train and the transport distance from the location of the train at the beginning of this calculation interval to the next stop. If $v1 \geq v2$, the train brakes to decrease its speed as soon as possible to a small value which is able to absolutely ensure the safety of its stop in the next station; if $v1 < v2$, the train coasts. Such a decision is made for each latter calculation interval till the train stops in security in the next station according to the $v1$ of the train in each of the latter calculation intervals and the $v2$ which is determined based on not only the location of the train at the beginning of each latter calculation interval but also the braking performance of the train.

The traction force of a train utilizing a certain ratio, that is, r%, of its full traction power in a calculation interval is determined by both the speed and the operating condition of this train, as explained by (2.1). When the train is coasting or braking, its traction force is 0 N:

$$f_k^r = \begin{cases} \dfrac{P_k^r}{v_{k-1}^{\mathrm{pr}}}, & \left(v - v_{k-1}^{\mathrm{pr}}\right) > C^{\mathrm{tm}} \text{ or } \left(v_k^{\mathrm{ul}} - v_{k-1}^{\mathrm{pr}}\right) > C^{\mathrm{ul}} \\ 0, & \left(v - v_{k-1}^{\mathrm{pr}}\right) \leq C^{\mathrm{tm}} \text{ or } \left(v_k^{\mathrm{ul}} - v_{k-1}^{\mathrm{pr}}\right) \leq C^{\mathrm{ul}}, \end{cases} \tag{2.1}$$

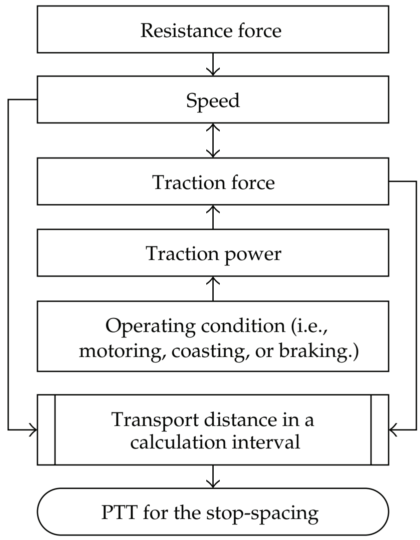

Figure 2: Simulation approach to calculate the PTT.

where f_k^r is the traction force of the train utilizing r% of its full traction power in the kth calculation interval, unit: N, P_k^r is the traction power of the train utilizing r% of its full traction power in the kth calculation interval, unit: W, v_{k-1}^{pr} is the speed of the train utilizing pr% of its full traction power at the end of the $(k-1)$th calculation interval, unit: m/s, v is the target speed of the train, unit: m/s, v_k^{ul} is the upper limit speed in the kth calculation interval, which is equal to v^{tm} when there is no requirement by the rail line, unit: m/s, C^{tm} is the permitted maximum difference between speed of the train and target speed, unit: m/s, and C^{ul} is the permitted maximum difference between speed of the train and upper limit speed which is equal to C^{tm} when there is no requirement by the rail line, unit: m/s.

As illuminated by (2.1) and (2.2), the speed of the train in a calculation interval is decided by the speed of the train at the end of the previous calculation interval, the traction force for the utilized proportion of its full traction power in this calculation interval, the target speed, the upper limit speed required by the rail line in this calculation interval, the mass of the train, and the resistance force from air, rail line, and so forth in this calculation interval:

$$v_k^r = v_{k-1}^{\mathrm{pr}} + \frac{f_k^r - f_k^L}{M} \times \Delta t, \tag{2.2}$$

where v_k^r is the speed of the train utilizing r% of its full traction power at the end of the kth calculation interval, unit: m/s, f_k^L is the resistance force in the kth calculation interval, unit: N, which is measured by (2.3), M is the mass of the train, unit: Kg, and Δt is the equivalent length of the calculation intervals, that is, 1.00 s, in this work:

$$f_k^L = \alpha_0 + \alpha_1 \times \left(v_{k-1}^{\mathrm{pr}}\right) + \alpha_2 \times \left(v_{k-1}^{\mathrm{pr}}\right)^2 + f_k^S, \tag{2.3}$$

where α_0, α_1, and α_2 are the coefficients determined by the body streamline design of the locomotive, the friction between the wheels and the rail, and so on, and f_k^S is the resistance from the ramps, bends, and so forth, of the rail line in the kth calculation interval, unit: N. Because of the afore-explained assumption of a hypothetically straight and smooth rail line, the special resistance force is 0 N in this study.

Different types of locomotives have respective traction performances to overcome the resistance force in their traction processes on the same rail line for the same transport work and the same target speed at the expense of different transport time. The transport distance of the train in a calculation interval is interpreted as (2.4). The PTT of the train between two neighboring stops is computed by the summation of all the calculation intervals which make the train complete successive transport distances constituting this stop-spacing:

$$d_k^r = \frac{v_{k-1}^{\mathrm{pr}} + v_k^r}{2} \times \Delta t, \tag{2.4}$$

where d_k^r means the transport distance of the train utilizing r% of its full traction power in the kth calculation interval, unit: m.

3. Analysis of Transport Efficiency

The PTT per 10,000 p-km of a train with the target speed of v between two stops is defined by (3.1) to evaluate its transport efficiency:

$$t_{ij}^v = \frac{T_{ij}^v}{\left(\sum_{q=1}^{\mathrm{tn}}\left(P_{ij}^{v,q} \times R_{ij}^{v,q}\right)\right) \times D_{ij}^v}, \tag{3.1}$$

where t_{ij}^v is the PTT per 10,000 p-km of the train with the target speed of v from station i to station j, unit: hour (h)/10,000 p-km, T_{ij}^v is the PTT of the train with the target speed of v from station i to station j, unit: h, tn is the total number of the railway cars forming the studied train, $P_{ij}^{v,q}$ is the number of the passenger seats or berths of the qth railway car forming the train with the target speed of v from station i to station j, $R_{ij}^{v,q}$ is the utilization ratio of the passenger seats or berths of the qth railway car forming the train with the target speed of v from station i to station j, unit: %, and D_{ij}^v is the transport distance of the train with the target speed of v from station i to station j, unit: 10,000 km.

The transport distance (unit: 10,000 km) from the nth stop ($S(n)$) to the $(n+1)$th stop ($S(n+1)$) ($n = 1, 2, \ldots, 20$) of the hypothetically straight and smooth rail line in this research is interpreted by (3.2):

$$D_{S(n),S(n+1)} = 5.00 \times 10^{-4} \times n. \tag{3.2}$$

The changes of the PTTs per 10,000 p-km of the passenger transports of the CLHP train hauled, respectively, by the SS3 and the SS8 between different stops along this hypothetical rail line with the increase of the target speed of the train are presented in Figures 3 and 4 correspondingly. It is first observed in Figure 3 that when the target speed of the train is lower than about 40.00 km/h, the PTTs per 10,000 p-km of the train hauled by the SS3 for different transport distances between neighboring stops decrease relatively fast with the increase of the target speed and the length of stop-spacing has minor influence upon the

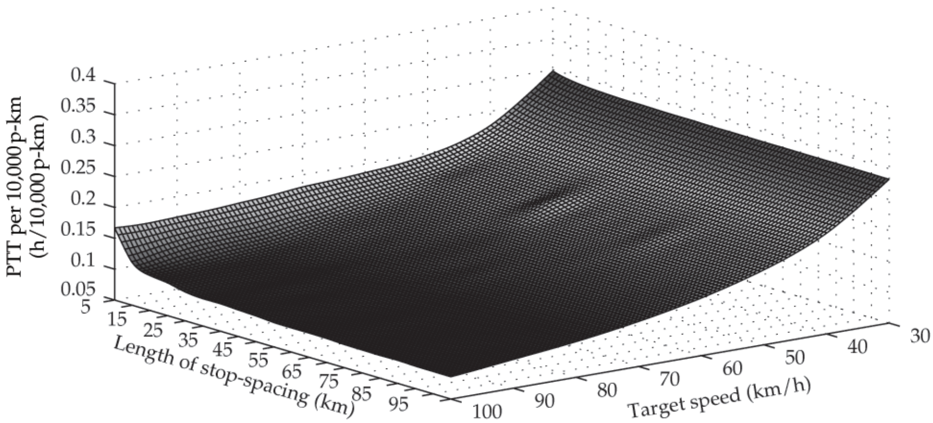

Figure 3: PTTs of the CLHP train hauled by the SS3.

PTTs per 10,000 p-km. If the target speed becomes higher than approximately 40.00 km/h, the decreases of the PTTs per 10,000 p-km with the improvement of the target speed slow down and start to further decelerate due to the decrease of the interstop transport distance especially below about 20.00 km. If the target speed is improved from 90.00 km/h, a comparatively very short stop-spacing (e.g., S01-S02) is able to cease the decrease of the PTT per 10,000 p-km with the increase of the target speed by stopping the acceleration of the train in this stop-spacing for its safe stop at the next station before its achievement of the target speed.

The changes of the PTTs per 10,000 p-km of the train hauled by the SS8 with the increase of the target speed for different interstop transport distances are shown in Figure 4. If the target speed is lower than around 40.00 km/h, the PTTs per 10,000 p-km of the train hauled by the SS8 decrease rapidly with the increase of the target speed and get little impact of the transport distances between stops. If the target speed is higher than some 40.00 km/h, the decreases of the PTTs per 10,000 p-km with the increase of the target speed of the train become slow. The interstop transport distances shorter than approximately 20.00 km at this time begin to evidently consume additional PTT per 10,000 p-km and such a trend becomes obvious with the increase of the target speed as well as the decrease of the length of stop-spacing. If the target speed increase from 90.00 km/h, the decreases of the PTTs per 10,000 p-km start to stop by following the ascending sequence of the transport distances between neighboring stops because of the previously explained stopped acceleration of the train before its achieving the target speed. Moreover, some target speeds (e.g., 90.00 km/h) for certain stop-spacings (e.g., S01-S02) make the speed of the train at the rail sites where the train begins to check the necessity of brakes before arriving at the next stop reach or exceed the permitted speeds by coincidence. As interpreted in Section 2, such a situation makes the speed of the train decrease as soon as possible to a small value to ensure absolute security of the transport. Thereafter, the train runs with this low speed till it arrives at the next stop, which causes the increases of some PTTs per 10,000 p-km especially for comparatively short interstop transport distances.

As to an unchanged utilization ratio of the passenger seats and berths of the studied CLHP train in China, it is found that the improvement of the target speed of the train below about 40.00 km/h decreases its PTT per 10,000 p-km rapidly and the length of stop-spacing at this time has very little effect on the PTT per 10,000 p-km. The decrease of the PTT per 10,000 p-km with the increase of the target speed starts to slow down if the target speed

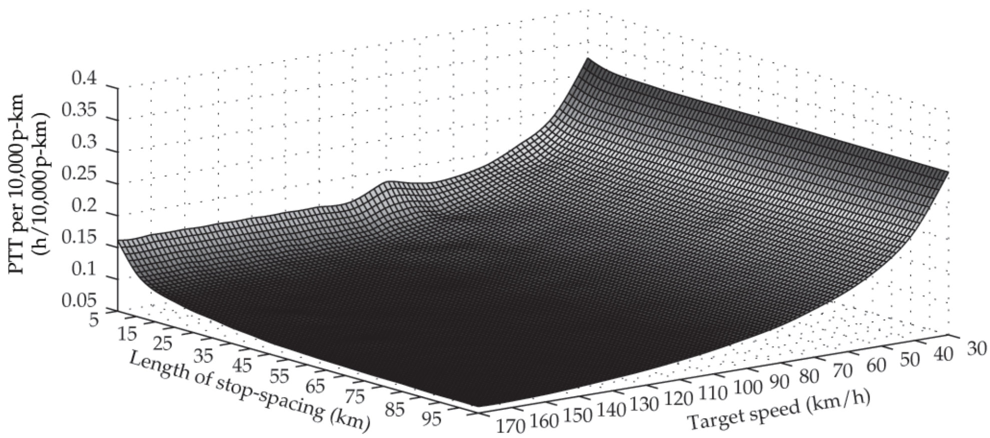

Figure 4: PTTs of the CLHP train hauled by the SS8.

becomes higher than around 40.00 km/h and begins to further decelerate with the decrease of the interstop transport distance especially below around 20.00 km. Such trends are able to be on the whole described by (3.3) according to curve fitting analyses:

$$t_{ij}^{v} = a \times v^{b}, \quad (a > 0), \ (-1 < b < 0). \tag{3.3}$$

If v is smaller than approximately 40.00 km/h or D_{ij}^{v} is bigger than about 20.00 km, the parameters of a and b in (3.3) verge on constants whose values are determined mainly by the general traction performance of the applied locomotive. If v is over some 40.00 km/h and D_{ij}^{v} is below approximately 20.00 km, the absolute values of a and b are remarkably increased with the decrease of D_{ij}^{v} as interpreted by (3.4) and (3.5):

$$a = c_1^a \times \ln\left(D_{ij}^{v}\right) + c_2^a, \quad \left(c_1^a > 0\right), \tag{3.4}$$

$$b = c_1^b \times \ln\left(D_{ij}^{v}\right) + c_2^b, \quad \left(c_1^b < 0\right), \tag{3.5}$$

where c_1^a, c_2^a, c_1^b, and c_2^b are constant parameters and each type of locomotives has its own set of values for these parameters because of the specific traction performances of different types of locomotives.

In addition, when the target speed of a train exceeds 90.00 km/h, its reachable maximum speed may much differ from its target speed due to the restriction of the transport distance between neighboring stops, which will have the PTTs per 10,000 p-km of the train for different targets speeds over a certain value, that is, v^s, the same to each other for the same stop-spacing. As revealed in Figures 3 and 4, v^s is decreased with shortening the stop-spacing and also affected by the traction performance of the locomotive.

4. Conclusions

Now it is able to be empirically confirmed that decreasing the length of stop-spacing from about 20.00 km obviously increases the transport time per passenger-kilometer of a CLHP train especially for a relatively high target speed over approximately 40.00 km/h. In contrast, the interstop transport distances longer than some 20.00 km have almost no effect on the transport efficiency of the train. Such changes follow the trends generally interpreted by the power function of (3.3). As a result, it is clear that the target speed of a CLHP train is unnecessary to be kept as a consistent value which is especially much higher than about 40.00 km/h for the discounted efficiency of the train's transport between its originating and terminal stops due to the effect of some short interstop transport distances which also cause intensive traction energy consumption [9, 13]. In other words, the target speed of a CLHP train providing the transport service on a railway line whose transport capacity has not been much used should be flexibly decided according to the length of each stop-spacing.

Due to data limitation, only the transports of a typically formed CLHP train hauled by, respectively, two major types of the locomotives in China on a hypothetically straight and smooth rail line are studied in this research to explore the effect of the length of the stop-spacing on the PTT per 10,000 p-km for different target speeds of the train. The impacts of the ramps, bends, bridges, tunnels, and so forth of different rail lines on the transport time per passenger-kilometer of the transports completed by more kinds of trains which are formed by various numbers of different types of railway cars should be analyzed together with the effect of different transport distances between neighboring stops, traction performances of varied types of locomotives, and so forth for different target speeds from a more comprehensive viewpoint to further improve the conclusions of this study in the future.

Acknowledgments

This study is financially supported by the National Basic Research Program of China (2012CB725406) and the National Natural Science Foundation of China (71131001; 71201006).

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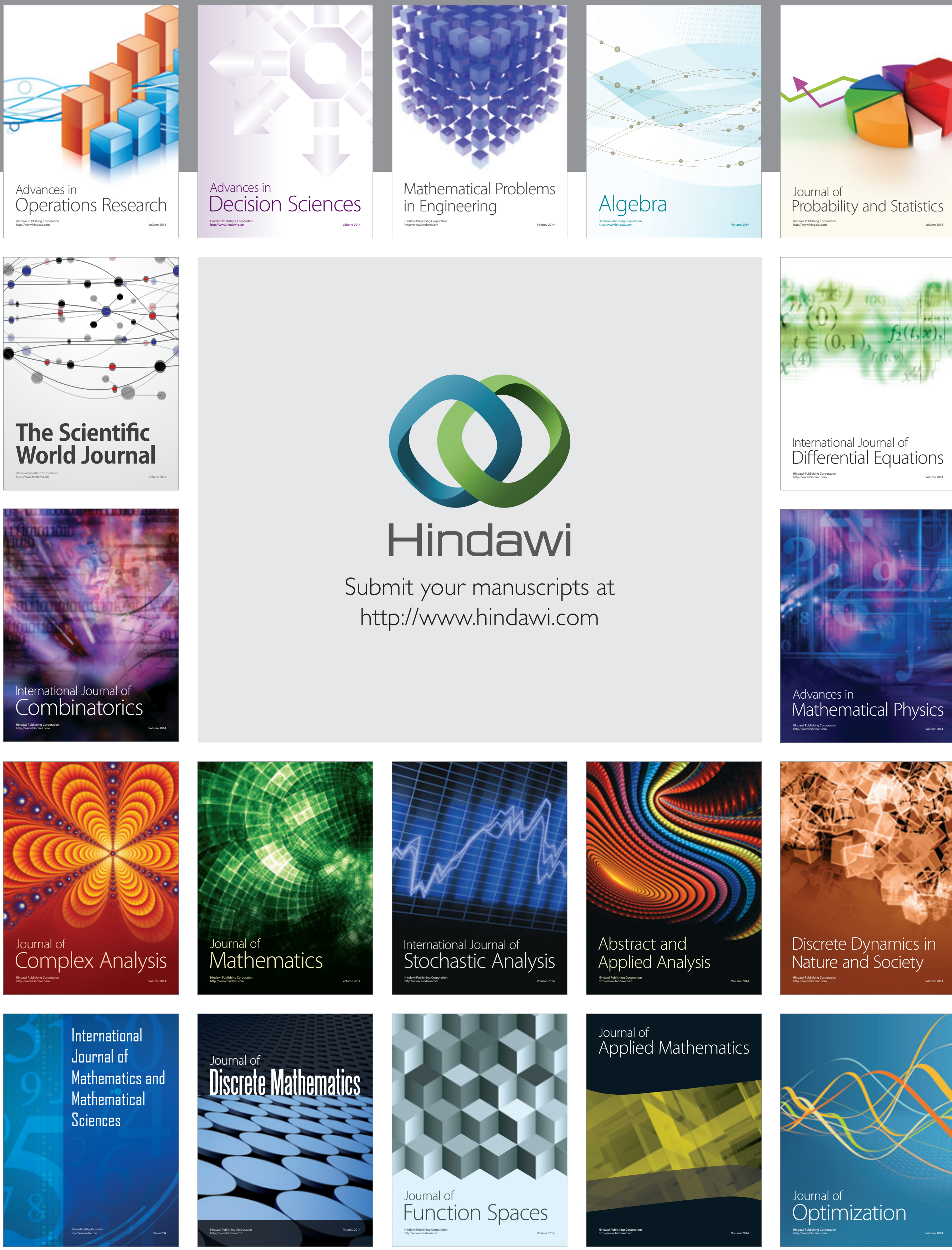
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