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Assessing Hyperloop Transport Capacity under Moving-Block and Virtual Coupling Operations.

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ABSTRACT

The Hyperloop is a concept of a ground transportation system consisting of capsules (called pods) traveling at very high-speeds in near-vacuum tubes. The hyperloop aims to be a fast, cheap, and sustainable alternative to short-haul flights and high-speed rail. The small pod size requires very high frequencies to respond to future high levels of passenger and cargo demands. Media and representatives of the emerging Hyperloop industry acclaim the Hyperloop as a very capacity-effective transport system, however there is no clear scientific evidence proving that. A theoretical investigation is therefore necessary to understand which capacity the Hyperloop could safely provide and whether that could satisfy the future transport demand. This paper provides a comparative analysis of the capacity that the Hyperloop can offer for several operational scenarios and different signalling systems, including Moving-Block and the advanced concept of Virtual Coupling. Results show that Moving-Block could achieve required transport capacity levels only if pods could use high deceleration rates likely to be unsafe and uncomfortable to passengers. Virtual Coupling is instead observed to be a more satisfactory operational concept that could address transport demand while respecting safety and comfort standards if reliable pod platooning technologies are available.

Keywords: Hyperloop capacity, Virtual Coupling, Moving-Block, High-speed transport.

INTRODUCTION

The Hyperloop is a conceptual mode of transport in which capsules (also called pods) travel at very high speeds in a reduced pressure tube. The proposed concept is claimed to achieve better performances in terms of travel time, costs, energy consumption and safety when compared to short-haul flights and high-speed rail (*1*). The hyperloop has also been reported (*1*) as a very capacity-effective system, despite there is no scientific evidence for that statement. Vehicles to be used in the Hyperloop will have indeed limited size to fit the tube meaning a reduced vehicle capacity to accommodate passengers and/or cargo. Because of the restricted vehicle capacity, Hyperloop shall rely on high frequencies to respond to the expected travel demand growth of passengers and freight. A deeper theoretical capacity investigation is hence needed to understand the actual transport capacity of the Hyperloop when realistic operational scenarios and safety constraints of the signalling system are considered.

Few studies exist about Hyperloop capacity analysis. Musk in the Hyperloop Alpha paper (*1*) reports a regular pod frequency of two minutes, which can be increased to a maximum of 30 s during peak hours. Decker et al. (*2*) compute the maximum safe pod frequency based on an absolute braking distance separation and assuming a deceleration rate of 1g, which leads to a maximum frequency of 30 s. Another interesting work was made by van Goeverden et al. (*3*) who perform a multi-criteria analysis indicating the Hyperloop as a premium transport mode given that the limited capacity would make ticket prices only affordable by exclusive passenger categories. Their conclusion however relied on a macroscopic capacity model that disregarded possible pod manoeuvres at junctions and detailed safety constraints due to the signalling system. They report a pod frequency of just five minutes, based on a deceleration rate of ~0.15g.

Some of the pod frequencies found in the literature report promising values. However, the high deceleration rates considered are likely to be unsafe and uncomfortable for the passengers. Moreover, there is no clear evidence if there will be advances in technology to safely achieve those reported deceleration rates. Furthermore, the existing literature on transport capacity of the Hyperloop system has been focused only on the simple case of plain lines excluding intermediate stops or junctions where multiple pods could merge/diverge. The actual Hyperloop transport capacity might hence be much lower than what has been so far reported if realistic pod manoeuvres at junctions/stations as well as safe signalling constraints are taken into account.

Existing literature has mostly assumed a separation between consecutive pods to be at least the absolute braking distance, i.e. the distance required for a capsule to brake from its current speed to standstill, although without specifying the type of signalling technology to achieve that separation. Even so, such a concept resembles Moving-Block (MB) operations already used in metro lines by means of the Communication Based Train Control (CBTC) (*4*) and specified for conventional railways by the ETCS Level 3 standard (not yet been implemented) (*5*). The reported high pod frequencies rely on high deceleration rates to brake in case the pod ahead suddenly stops. However, an advanced signalling concept known as Virtual Coupling (VC) has been proposed in the railway field in which pods could follow each other at distances shorter than the absolute braking distance to eventually move synchronously in radio-linked platoons which could be treated as a single vehicle (*6*). Under VC pods could hence couple/decouple on-the-run by first following each other at a relative braking distance (i.e. the distance to brake from current speed to the speed of the pod ahead) until they synchronize their speed with the pod ahead to form a platoon. Pods moving in a platoon are separated only by a safety margin which depends on the running speed and the difference in braking rates of the pods. Such a concept might represent an attractive alternative to achieve satisfactory pod frequencies while keeping deceleration rates at levels that are safe and respect passenger comfort.

This paper aims to cover the existing gap in the literature by assessing the transport capacity which the Hyperloop can safely provide for all possible operational scenarios under both MB and VC signalling concepts.

HYPERLOOP CAPACITY ASSESSMENT METHODOLOGY

A two-steps methodological framework has been set up (**Figure 1**) to assess the Hyperloop transport capacity for several pod manoeuvres on different infrastructure layouts, signalling and switching technologies as well as station configurations. In the first step, a detailed analysis of pod dynamics is performed. In particular, the microscopic railway traffic simulation tool EGTRAIN (*12*) has been extended to model Hyperloop pod dynamics and accurately describe pod braking curves which are here obtained by reversing the thrust of the motors. Inputs to the microscopic model include characteristics of the capsule (e.g. length, mass, tractive effort speed curve) as well as the infrastructure (e.g. track length, gradient, curvature radii, junction layout).

The second step draws on detailed pod dynamics computed in Step 1 to implement an analytical capacity assessment method to assess Hyperloop capacity for different configurations of the system. Specifically, the analytical assessment builds on the UIC Code 406 blocking time compression (*7*) which is a consolidated method in the railway field for the evaluation of infrastructure occupation. Capacity is here assessed in terms of the minimum time headway that can be safely allowed between two consecutive pods for each of the following system configurations which constitute an input to the model:

- Operational scenarios: which define a set of possible pod manoeuvres on relevant network locations such as plain Hyperloop tracks, merging and diverging junctions. Operational scenarios also include two different service patterns of i) pods having intermediate stops along the track as well as ii) non-stopping pods only delivering a direct end-to-end connection between the terminal stations of the Hyperloop corridor.
- Signalling systems: where both MB and the advanced signalling concept of VC are considered.
- Direction switching technologies: including two different systems allowing a direction change at merging/diverging junctions. Specifically, the considered systems are a traditional mechanical moving switch and an innovative fixed magnetic switch concept (*8*).
- Station layout: for the operational scenarios with stops, the capacity is assessed for the case where intermediate stations have one single airlock but also when at least two airlocks are available, in which case more than one pod can load/unload customers at the same time.

The developed analytical model provides as output the minimum time headway between two consecutive pods for each of the Hyperloop system configurations, i.e. a given combination of operational scenario, signalling system, switching technology and station layout. Obtained minimum headways are then translated in terms of transport capacity and provided as both maximum hourly number of pods and passengers that could be transported. Transport capacity results produced by our framework are then compared with the one of alternative modes of transport, namely high-speed railways and air passenger transport.

A detailed description of inputs/outputs and methods employed is provided in the following subsections.

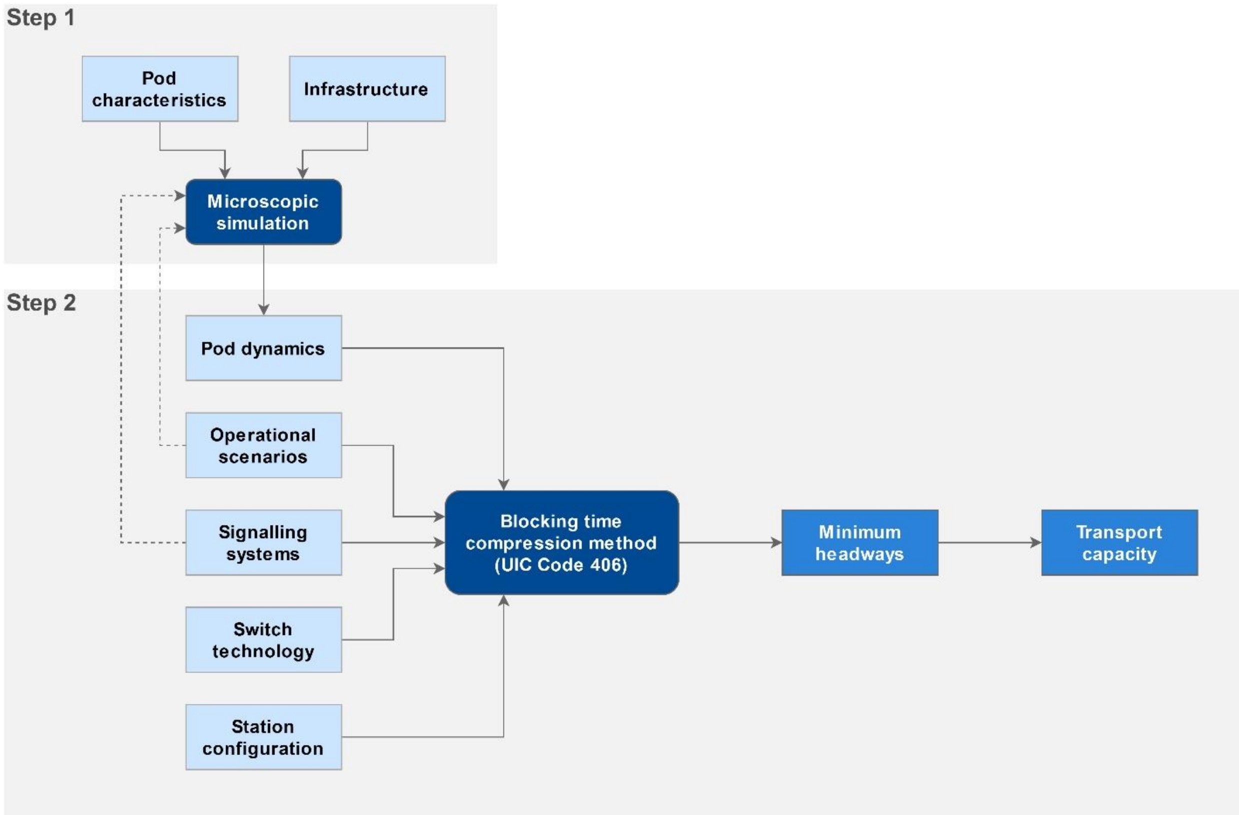

Figure 1. Overview of the methodology used to assess the Hyperloop transport capacity

Capsule dynamics

The simplest approaches to model the capsule dynamics assume constant acceleration and deceleration rates. To obtain more realistic results, this work considers a detailed description of the propulsion system and the motion resistances. The fact the Hyperloop is still a concept has led to many different concepts for its various components. The propulsion system is not an exception and various possible configurations can be found in the literature (*9*, *10*). This work is based on a single configuration which is a magnetically levitated capsule propelled by a linear synchronous motor as proposed by Choi et al. (*9*).

Braking curve

The braking curve of the pod was simulated by extending the EGTRAIN microscopic railway traffic simulation model (*11*), which is based on a discrete-time solution of Newton's motion differential equations (*12*). The set of mathematical expressions capturing the train dynamics were adjusted to include the behaviour of the capsule. The model considers the main characteristics of the pod based on the design proposed in (*9*), namely mass, length, maximum speed, tractive effort-speed curve and motion resistances. The motion resistances that depend on speed include aerodynamic drag (tube pressure of 0.001 atm) and magnetic resistance. Also, an analysis has been performed to identify impacts on the pod's braking curve of different tube gradients considering a slope of -3‰, +3‰ as well as a flat track. The braking action is assumed to apply a reverse thrust produced by reversing the motor, instead of using a constant braking rate. It is assumed the motor can produce the same thrust in both directions.

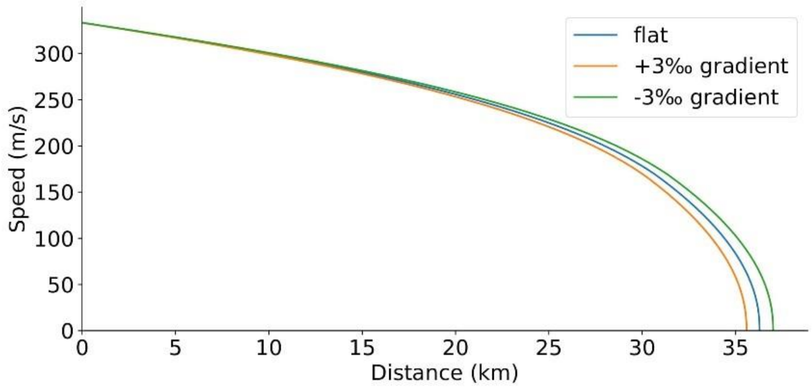

Figure 2 Pod braking curves for various track gradients

Simulated run

In addition to obtaining the braking curve to be used when assessing the transport capacity, the microscopic simulation was utilized to simulate a run of two pods in a representative Hyperloop corridor having a total length of 600 km between two termini stations. The second pod departs 360 s later, which is enough to let the second capsule running without being constrained by the pod ahead. **Figure 3** shows the simulated time-distance diagram of the two capsules. The slope of the curves varies along the tube as the maximum speed changes stepwise (480, 890 and 1200 km/h) both at the beginning and the end of the tube. Pods travel with an average speed of 924 km/h.

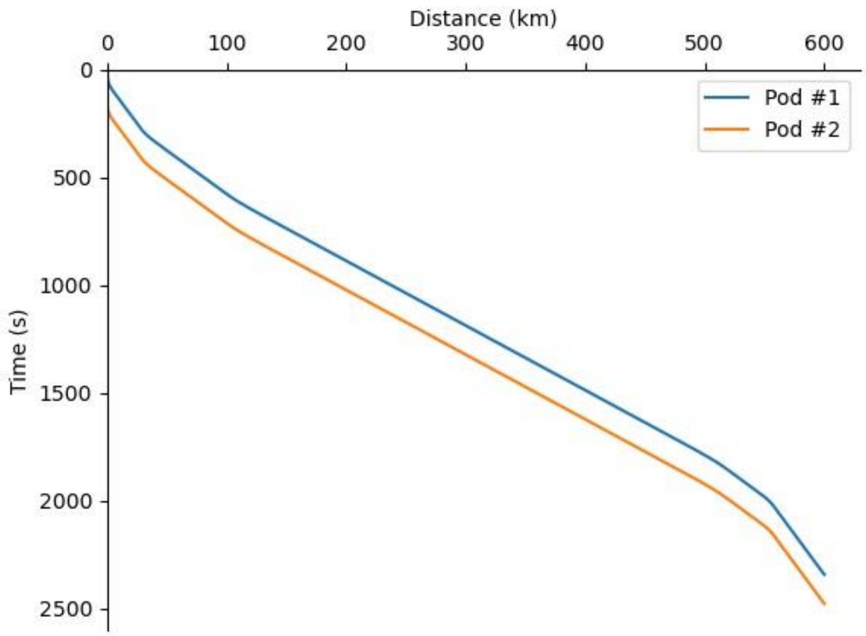

Figure 3 Time-distance diagram of two pods running in the same tube

Operational Scenarios

Hyperloop networks will likely consist of links between main cities possibly with intermediate stops and connections to other lines and branches. Junctions allowing pods to merge/diverge from/to different destinations as well as intermediate stations will likely be potential bottlenecks constraining the maximum transport capacity of the Hyperloop. Our study hence analyses different possible types of infrastructure layouts and the corresponding type of vehicle manoeuvres which could be found on a Hyperloop corridor. A combination of infrastructure layout and a manoeuvre is here defined as an operational scenario. A total of six operational scenarios have been defined considering non-stopping and stopping Hyperloop services on a plain line, a merging and a diverging junction (**Figure 4**). The plain line consists of two consecutive pods traveling in the same direction and the same tube. The second manoeuvre is a merging junction where one of the capsules enters the main tube from a branch. It is assumed the pod coming from the branch crosses the merging junction as first. For the stopping service, both pods stop at the platform located 3 km ahead of the junction. Finally, the diverging junction is a link from the main tube to a branch. For the non-stopping service, the first pod diverges to the branch while the capsule behind continues on the main tube. In the diverging junction with stop, the capsule ahead continues on the main tube and stops at the platform while the pod behind diverges to the branch without stopping. The platform is located 3 km after the junction, in the main tube.

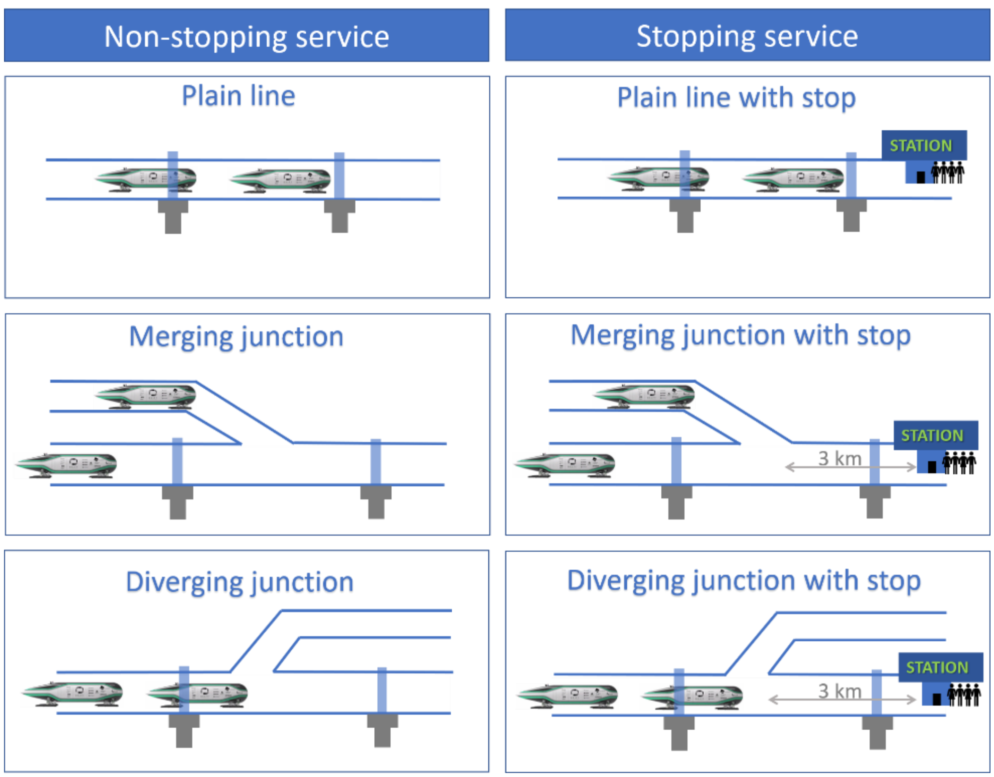

Figure 4 Schematic operational scenarios to be evaluated

For the merging/diverging junctions, the headways are calculated at the junction. It is assumed a speed limit of 1200 km/h on the main tube, while the speed of the capsule taking the switch depends on the specific switch technology considered. For the plain line without stop, the headway is computed in a section where the speed limit is 1200 km/h. For the plain line with stop, the arrival headway is considered.

In the railways, capacity bottlenecks are commonly due to junctions, as switches are safety-critical elements which generally require trains to slow down to avoid derailments. In the case of the Hyperloop, it is not clear which technology will be adopted to let pods switch over merging and diverging tracks. Hardt Hyperloop (*8*) has introduced the concept of an innovative magnetic switching technology having no moving infrastructure elements, claimed to allow pods changing direction without speed reductions. However, such a technology has not yet been proved on a full-scale test track. Given the nonexistence of a consolidated and proved Hyperloop switching technology, this study will investigate the capacity for both the case of classical mechanical switches with moving beams (as adopted in railways) as well as innovative high-speed fixed magnetic switches. Therefore, pod manoeuvres over diverging and merging junctions consider the existence of two different types of direction switching technologies: i) a Fixed Magnetic Switching technology (FMS) like the one proposed by Hardt (*8*) which does not require speed reductions and setup times to move and lock the switch, ii) a Moving Mechanical Switch (MMS) like those traditionally used in the railways which requires a given setup time (assumed here to be 4 s) to move, set and lock the switch in the correct direction for the pod. Given that an MMS could fail to move in time and/or in a safe direction between two consecutive pods, an absolute braking distance separation will need to be imposed before this type of switches either under MB or VC at junctions. Taking into account the FMS technology is still in development, this study considers a case without speed reduction but also speed restrictions of 750 km/h and 100 km/h. Regarding the MMS, a single case is studied, where a speed restriction of 100 km/h is imposed as this is the maximum speed currently allowed on traditional mechanical railway switches.

Also, stations are a relevant location when studying capacity. As it happens with switches, the operational conditions at stations are still not clear. Differently from the railways, the Hyperloop will operate in a quasi-vacuumed environment, hence airlocks are needed at stations to let passengers alight/board the pod while keeping the reduced pressure within the tube (*1*). The capacity at stations will be undoubtedly influenced by the number of pods that can embark/disembark passengers and/or cargo at the same time. If no more than one pod is allowed at the same time, the station capacity will be strongly affected. This is very important for the signalling systems considered. For both MB and VC, our capacity investigation assumes two possible cases. For the first case, there is only one chamber so that a platform can be occupied by one single pod, so that if it is occupied, the next pod must wait until the capsule ahead leaves the platform. For the alternative case with two chambers, two pods can stop one behind each other at the same platform to embark/disembark passengers and/or freight while keeping a safe separation of 50 m in between.

Signalling Systems

The operating conditions of the Hyperloop require advanced signalling systems so that high capacities can be achieved while guaranteeing the safety of objects and passengers. The Hyperloop will likely build on signalling concepts not far from those currently under investigation in the railway industry given that both are a guideway transport mode. The concept of MB signalling allows consecutive trains to be separated by an absolute braking distance. This way, a vehicle can safely stop even if the vehicle ahead suddenly stops, avoiding a collision. The proposed concept of VC introduces a Vehicle to Vehicle communication layer allowing the exchange of speed and acceleration information so that a pod can approach one ahead at a relative braking distance to eventually move synchronously by forming a radio-linked platoon. When traveling in a platoon, pods would keep a safety margin function of the running speed and the difference between braking rates of consecutive pods.

Two modes will be evaluated to assess the capacity impacts of VC, namely the Coupling/Decoupling mode ($VC_{C/D}$) and the Platooning mode (VC_P). By default, it is assumed a capsule is running independently under MB. From there, the transition to the coupling mode happens when a capsule is approaching the pod ahead and the next stretch of their routes is the same. During this mode, the capsule behind will try to reach the speed of the pod ahead, always respecting a safety margin between vehicles. If the pod behind is able to attain that speed, the pods transit to the platooning mode. While traveling in a state of coupled running, two transitions can occur: unintentional or intentional decoupling. The first happens when the pod behind cannot hold the same speed of the capsule ahead, because of power limitations and/or higher motion resistances. After this transition, the pod behind will try to catch up again with the capsule ahead. If the conditions are met again, they transit to the platooning mode. From the platooning mode, an intentional decoupling transition may also occur. This happens when coupled vehicles approach a diverging junction where the leading pod takes a different route. After the capsule has been intentionally decoupled from the pod ahead, it will run under MB until conditions for coupling to another pod are met. A detailed description of VC operational states and transitions is provided by Quaglietta et al. (*13*).

Given that the pods will reach very-high speeds, they will be driven by an Automatic Train Operation (ATO), regardless of the signalling system used. ATO is even more necessary for operating pods moving in platoons under VC.

Blocking time compression method for capacity assessment

As already mentioned, the calculation of minimum headways for each system configuration is performed based on an adaptation of the blocking time compression method of the UIC Code 406 (*7*) which is a consolidated approach in the railway literature. The blocking time theory builds on the concept that a given section of track can be occupied by one and only one vehicle per time. The total time a track section is occupied (and hence blocked) by a pod is the sum of the following terms (**Figure 5**):

- Setup time: the time to set the route. In the case of the Hyperloop, this term will only be included when considering merging/diverging junctions equipped with traditional moving switches where the setup time is the time to move, set and lock a switch in the correct direction for a pod.
- Driving reaction time: usually the time for the driver to see and react to a signal aspect. Since the Hyperloop is an autonomous system, this term is simply the ATO reaction time.
- Approaching time: the time needed by a pod to approach a given track section ahead. For the Hyperloop, it is the time to cross the absolute or relative braking distance for MB or $VC_{C/D}$, respectively, or zero for VC_P.
- Running time: the time to cross a track section of a given length (called block section in railway literature) which the signalling system supervises so that only one vehicle at a time can occupy it. In the concept of Moving-Block operations, the length of a block section becomes infinitesimal since the track section supervised by the signalling system moves along with the vehicle. Such an assumption however does not apply to movable parts of the track such as switches which shall still be considered as fixed block sections. A merging

or a diverging pod cannot indeed occupy a switch unless the previous pod has fully cleared it and the switch has been moved, set and locked in the correct position. For this reason, in our model the running time term is only considered over switches but it is assumed to be zero instead on normal tracks.

- Clearing time: the time needed to clear a block section with the length of the pod.
- Release time: the time to release a block section that is considered to be the communication delay to transmit safety-critical information (such as movement authority and/or speed/acceleration of pods) between consecutive pods and/or the ground traffic control centre.

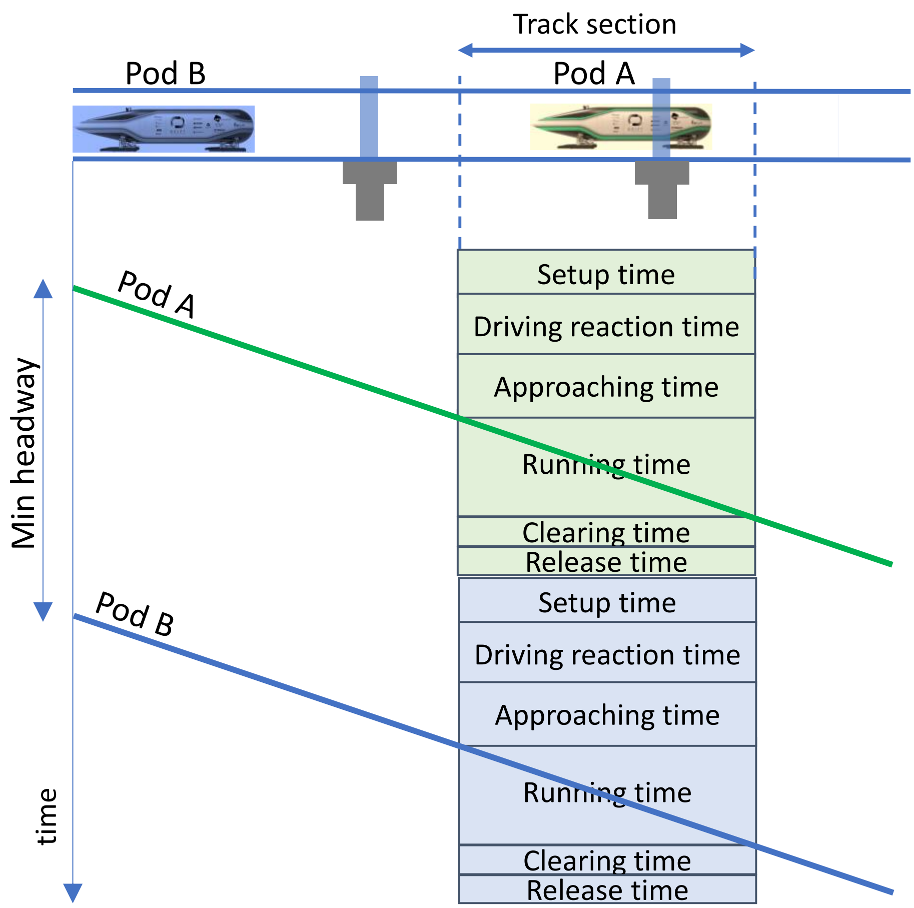

Figure 5 Method to calculate the time a track section is occupied by a pod

As illustrated in **Figure 5**, the minimum time headway is therefore identified as the minimum time distance that can be allowed between two consecutive pods so that their blocking times are not overlapping**.**

The values used for the setup times depend on the specific type of direction switching technology considered. In particular, the setup time has been assumed to be 4 s if a traditional MMS switching technology is used and 0 if an FMS is instead adopted. This means that in our model a mechanical switch will need 4 s to be moved, set and locked in the right direction for a crossing pod.

The reaction time is assumed to have a constant value $t_{reaction} = 0.5$ s in any system configuration. The ATO reaction time is considered independent from a particular system combination of signalling and switching technologies.

The values of the approaching and release times depend on the type of signalling and communication system adopted. Specifically, the approaching time is:

$$t_{approach} = \begin{cases} t_{ABD}, & if\ MB \\ t_{RBD}, if\ VC_{C/D}, \\ 0, if\ VC_P \end{cases} \tag{1}$$

where t_{ABD} and t_{RBD} are the time to cover the absolute and relative braking distance, respectively. These times are calculated based on the pod dynamics obtained from the microscopic simulations.

The release time is assumed to account for the communication delay to transmit safety-critical information. In MB, $t_{release} = 2$ s since in railway literature (*5*) this is an average time interval between two consecutive updates of the Movement Authority (i.e. the maximum distance a vehicle can safely cross) from a track-side radio control centre to a rail vehicle by using a GSM radio connection. In the case of VC_P instead $t_{release} = 0.02$ s given that this is a typical value observed in automotive literature (*14*) for cooperative vehicles communicating to each other. If VC_C then $t_{release} = 2.02$ s, since the communication delay accounts for the time needed to receive the Movement Authority from the track-side control centre and, on top of that, the vehicle-to-vehicle communication delay. For this mode, the pod behind needs to exchange kinematics information with the pod ahead. On the other hand, if VC_D then $t_{release} = 2$ s since the pod behind just needs to receive the Movement Authority from the track-side control centre indicating the location of the diverging switch.

To increase capacity the Hyperloop will likely be equipped with a Moving-Block signalling system without a segregation of the infrastructure in block sections (as traditionally instead implemented in railways). This is the same as saying that in a Moving-Block setup, block sections will have an infinitesimal length on the plain track while instead some kind of segregation is still needed at junctions, especially if they are equipped with MMS. For instance, in a junction equipped with a MMS, a pod cannot indeed cross the junction until the switch has been set and locked in the correct direction after that the previous pod has cleared the junction. In advantage of safety, we also consider that such a segregation at junctions is applied in the case of a FMS, although we assume a null switching time, given that no moving infrastructure elements exist. For this reason, the running time on sections on the plain track will be considered $t_{running} = 0$ (given the infinitesimal length of the section) while it will account for the time to cross the entire length of the switch (assumed to be 100 m for both merging and diverging junctions) at the speed simulated for the pods at the junction.

The clearing time $t_{clearing}$ is instead computed as the time a pod takes to release a section of the track with all its length (35 m) at the speed simulated for the pods at a given location.

CASE STUDY

The capacity that the Hyperloop can safely provide has been here computed for the different combinations of operational scenarios illustrated in **Figure 4**, as well as the described configurations of the switching technology, the signalling systems and the station layouts.

Capacity analysis

The comparative capacity analysis was performed for all the relevant combinations of operational scenarios and technological configurations reported in the Methodology for MB signalling as well as the two VC modes ($VC_{C/D}$ and VC_P). The capacity was assessed in terms of the time headway between consecutive capsules, where the highest capacity values correspond to the lowest time headways. The calculations considered the braking curve shown in **Figure 2** for the case of a flat track. For all cases, an ATO reaction time of 0.5 s was assumed. Also, a fixed safety margin has been considered between pods which is 200 m if pods are moving and 50 m if instead pods are queueing behind each other when stopping at the same station platform. A capsule length of 35 m is considered. The dwell time considered to embark/disembark passengers at stations is 120 s.

TABLE 1 shows the results obtained for all the combinations studied. For the non-stopping plain line, VC can greatly improve capacity over MB. The time headway reduces from 112.1 s under MB to just 1.2 s under VC_P. For the $VC_{C/D}$ mode, the two pods travel at different speeds and the separation respects the relative braking distance. For this mode, it is assumed pods travel at 1200 km/h (behind) and 750 km/h (ahead). This speed difference results in a substantial increase of the headway between pods when compared to VC_P.

TABLE 1 Time headways (in s) for all the combinations studied (switch speed reduction indicated in parentheses, in km/h)

Operational scenario	Switch type	MB	$VC_{C/D}$	VC_P
Plain line		112.1	84.5	1.2
Plain line with stop (one chamber)		313.1	228.3	128.1
Plain line with stop (two chambers)		185.5	100.7	0.5
Merging junction	FMS	112.4	3.5	
	FMS (750)	112.6	85.0	
	FMS (100)	116.8	116.5	
	MMS (100)	120.8	120.8	
Merging junction with stop	FMS	148.4	139.4	
	FMS (750)	148.4	139.4	
	FMS (100)	152.1	151.8	
	MMS (100)	156.1	156.2	
Diverging junction	FMS	112.4	3.5	
	FMS (750)	112.6	85.0	
	FMS (100)	116.8	116.5	
	MMS (100)	120.8	120.8	
Diverging junction with stop	FMS	113.0	104.0	
	FMS (750)	130.0	121.0	
	FMS (100)	177.7	177.3	
	MMS (100)	181.7	181.7	

For the plain line with a stop, the arrival headway is considered, i.e. the difference between the times the capsules actually stop at the platform. The highest capacity values are obtained for VC_P and two chambers since the arrival headway (0.5 s) simply accounts for the communication delay and ATO reaction time. Differently, VC_C and MB require also the time for the pod behind to cross the relative and absolute braking distance, respectively. When there are two chambers, two pods are allowed to enter the platform one behind each other and perform passenger alighting/boarding operations simultaneously. In the case that a single airlock is present, the second pod would instead need to wait for the first one to complete embarking/disembarking operations before being able to board/alight passengers. For the merging junction without stop, the configuration considering the FMS without speed reduction is similar to the plain line without a stop, since the capsules do not need to slow down. So, if such technology will be available, it will have a major impact in terms of capacity. The experience from the railways as shown how junctions are relevant capacity bottlenecks, as the cases here with speed reductions evidence. The results for this manoeuvre demonstrate that VC with the FMS technology can achieve minimal time headways of 3.5 s, while the headway for MB is 112.4 s for the same switch technology. On the other hand, if junctions would require considerable speed reductions, VC no longer introduces relevant benefits over MB since differences between absolute and relative braking distances tend to become marginal. This is also what happens for the non-stopping diverging junction.

The introduction of a stop after the merging junction leads to a more restrictive scenario than the non-stopping situation. For all cases, the pod behind needs to cross the junction at most with the speed needed to standstill at the platform (~450 km/h). The fact both pods need to stop and the capsule ahead will cross the junction at a low speed (~450 km/h or less depending on the switch) leads to distance separations close to the absolute braking distance. For this reason, VC introduces very little benefits over MB.

The time headways for the stopping merging and diverging junction are different. Since in the diverging manoeuvre only the first pod stops, the pod behind does not need to slow down to stop, therefore its speed is restricted only by the switch. The lowest headways for the merging junction with stop are 148.4 s for MB and 139.4 s for VC, while these are 113.0 s and 104.0 s for the diverging junction with stop, respectively.

Analysis of the most critical situations

Under MB and for two chambers, the maximum time headway obtained was 185.5 s, for the arrival headway in the stopping plain line. This is explained by the fact an absolute braking distance has always to be respected between pods. When the first capsule arrives, the other has still to brake over that distance. VC provides here an enormous advantage by allowing pods to stop almost at the same time. If a single chamber is available, the arrival headway increases significantly (313.1 s for MB and 128.1 s for VC_P), since the pod behind must wait for the capsule ahead to leave the chamber. Also for the plain line without stops, VC leads to a much higher capacity, again because pods can travel much closer in the platooning mode. However, the advantages of VC might be almost vanished at merging/diverging junctions, depending on the switch technology. If speed restrictions are imposed at junctions to allow pods to safely cross switches then the capacity advantage of VC over MB becomes marginal given that relative and absolute braking distances become comparable, especially for very restrictive speed limitations. In the case of an FMS not requiring speed limitations and the imposition of an absolute braking distance separation, VC would instead provide greater capacity improvements by allowing pods to move synchronously in platoons at a headway of 1.2 s, for the case of junctions without stops.

Overall system configuration analysis

The analysis of the different combinations has shown how these impact the capacity the Hyperloop can safely provide. In order to make a global comparison, the average time headways over all operational scenarios were considered for the signalling systems/modes and technological configurations (switch type and the number of chambers at stations). **Figure 6** shows that VC outperforms MB. The FMS technology allows a significant reduction of time headways when compared to MMS. For all cases, the existence of a second chamber decreases substantially the time headways. The reduction is significant for VC_P, from 64.7 s to 0.9 s. The highest capacity values are achieved by combining VC with the FMS technology and two chambers.

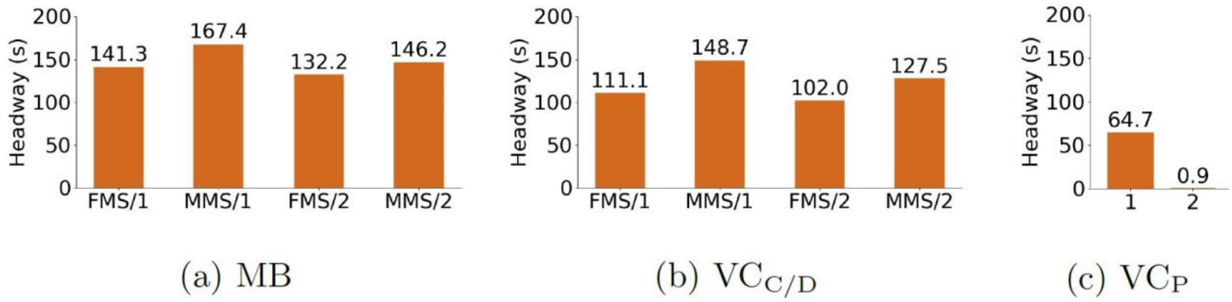

Figure 6 Average time headways for different combinations of signalling system/mode, switch technology and number of airlocks/chambers at stations

This study shows that VC could provide substantial capacity improvements with respect to MB. The greatest improvements are obtained if VC could always be operated in the platooning mode, where an average time headway between pods of only 0.9 s could be achieved if an FMS is installed and considering two chambers. Such a setup would provide 4126 pods/h meaning 123780 pax/h/direction per tube. For the same switch technology and number of chambers, MB could only reach an average headway of 132.2 s meaning 27 pods/h and 810 pax/h/direction per tube. Van Goeverden et al. (*3*) estimated the transport capacity provided by the main alternatives to the Hyperloop, which corresponds to 9600 pax/h for the high-speed rail and 312 pax/h for the air passenger transport. This study shows that the Hyperloop could largely exceed those values for the best technological configuration of virtually coupled platoons of pods, stations having multiple airlock/chambers to embark/disembark passengers simultaneously on/from different pods and junctions equipped with fixed magnetic switches requiring no speed reductions at the approach. This comparison of transport capacity for different transport modes and system configurations is summarized in **TABLE 2**.

TABLE 2 Comparison of transport capacity for different transport modes and system configurations

Transport mode and system configuration	**Hourly transport capacity (veh/h)**	**Hourly transport capacity (pax/h)**
Hyperloop with platooning, FMS and multiple station airlocks	4126	123780
Hyperloop with MB, MMS and single station airlock	27	810
Airplane		312
High-speed railway		9600

CONCLUSIONS

This work provides a wide capacity analysis of the Hyperloop system for different signalling systems and considering several operational scenarios. Since the Hyperloop is still a concept for a new mode of transport, many different technologies have been proposed and it is not clear which might be available. Therefore, the comparative analysis made included various possibilities.

The analysis has shown the concept of Virtual Coupling as the most suitable signalling system as it greatly reduces the time headways between capsules, therefore increasing capacity. The fact capsules are separated by a relative instead of an absolute braking distance means very short time headways can be achieved while using this technology. However, the benefits provided by such an innovative concept might become insignificant at junctions, depending on the switch technology. If a concept like the Fixed Magnetic Switch proposed by Hardt Hyperloop (*8*) would be available, high capacity values can be expected, with very short distance separations between consecutive pods. When running as a platoon, the time headway can be as short as 1.2 s.

This study shows that the reference headway values of 30 s claimed in the Hyperloop Alpha paper of Elon Musk (*1*) are not safely achievable with a simple MB signalling technology but can only be achieved if Virtual Coupling operations are equipped in combination with innovative switching technologies such as Fixed Magnetic Switches. The only way MB might achieve those headways during peak hours would be by using braking rates of the pods that exceed 1g, which are unsafe and uncomfortable to passengers.

However, on more complex networks having stations along the tube and junctions with stops, such values cannot be achieved even for the best combination of technologies studied. Furthermore, stations can severely reduce the capacity of the system in case pods are not allowed to stop at the same platform and embark/disembark passengers and cargo simultaneously. Unless more platforms can be used, each capsule would have to wait for the pod ahead to complete dwelling operations.

Further steps of this work should consider a wider range of possibilities for the Hyperloop system, e.g. in terms of the propulsion system. Also, studying capacity using simulation would allow a better comprehension of the dynamic interaction between vehicles, especially if more capsules and on-the-run platoon composition/decomposition under Virtual Coupling and failures/delays of the vehicle-to-vehicle communication are considered. Additionally, future research will investigate the effect that different braking rates of consecutive pods could have on capacity.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: R. Mendes Borges and Egidio Quaglietta have both contributed to the study conception and design, analysis and interpretation of results, manuscript preparation and revision. R. Mendes Borges has, in addition, collected necessary data and run the simulations.

REFERENCES

1. SpaceX. Hyperloop Alpha Document. 2013, p. 58.
2. Decker, K., J. Chin, A. Peng, C. Summers, G. Nguyen, A. Oberlander, G. Sakib, N. Sharifrazi, C. Heath, J. Gray, and R. Falck. Conceptual Feasibility Study of the Hyperloop Vehicle for Next-Generation Transport. *AIAA SciTech Forum - 55th AIAA Aerospace Sciences Meeting*, 2017, pp. 1–22. https://doi.org/10.2514/6.2017-0221.
3. van Goeverden, K., D. Milakis, M. Janic, and R. Konings. Analysis and Modelling of Performances of the HL (Hyperloop) Transport System. *European Transport Research Review*, Vol. 10, No. 2, 2018. https://doi.org/10.1186/s12544-018-0312-x.
4. Pascoe, R. D., and T. N. Eichorn. Robert D. Pascoe and Thomas N. Eichorn. *IEEE Vehicular Technology Magazine*, No. December, 2009, pp. 16–21. https://doi.org/10.1109/MVT.2009.934665.
5. Theeg, G., and S. Vlasenko. Railway Signalling and Interlocking. *International Compendium. Hamburg, Eurail-press Publ*, Vol. 448, 2009.
6. Quaglietta, E. Analysis of Platooning Train Operations under V2V Communication-Based Signaling: Fundamental Modelling and Capacity Impacts of Virtual Coupling. *Transportation Research Board: The TRIS and ITRD database*, 2019.
7. UIC Leaflet. 406. Capacity. *International Union of Railways*, 2004.
8. Hyperloop Switch. hardt.global/technology-development. Accessed May 22, 2020.
9. Choi, S. Y., C. Y. Lee, J. M. Jo, J. H. Choe, Y. J. Oh, K. S. Lee, and J. Y. Lim. Sub-Sonic Linear Synchronous Motors Using Superconducting Magnets for the Hyperloop. 2019.
10. Ji, W. Y., G. Jeong, C. B. Park, I. H. Jo, and H. W. Lee. A Study of Non-Symmetric Double-Sided Linear Induction Motor for Hyperloop All-In-One System (Propulsion, Levitation, and Guidance). *IEEE Transactions on Magnetics*, Vol. 54, No. 11, 2018, pp. 2018–2021. https://doi.org/10.1109/TMAG.2018.2848292.
11. Quaglietta, E. A Simulation-Based Approach for the Optimal Design of Signalling Block Layout in Railway Networks. *Simulation Modelling Practice and Theory*, Vol. 46, 2014, pp. 4–24. https://doi.org/10.1016/j.simpat.2013.11.006.
12. Hansen, I. A., and J. Pachl. Railway Timetabling & Operations. *Eurailpress, Hamburg, Germany*, 2014.
13. Quaglietta, E., M. Wang, and R. M. P. Goverde. A Multi-State Train-Following Model for the Analysis of Virtual Coupling Railway Operations. *Journal of Rail Transport Planning and Management*, No. xxxx, 2020, p. 100195. https://doi.org/10.1016/j.jrtpm.2020.100195.
14. Wang, M., W. Daamen, S. P. Hoogendoorn, and B. Van Arem. Cooperative Car-Following Control : Distributed Algorithm and Impact on Moving Jam Features. Vol. 17, No. 5, 2016, pp. 1459–1471.