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Hyperloop and Aerodynamics

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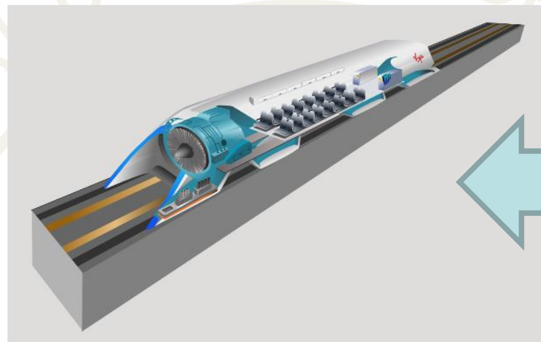
Introduction

- **What is Hyperloop?** [WIKIPEDIA]
  - tradename and a registered trademark of the *Space Exploration Technologies Corporation*(SpaceX) for the high speed transportation of passengers and goods in tubes in which capsules are propelled by linear induction motors and air compressors.
  - Musk first mentioned that he was thinking about a concept for a "**fifth mode of transport**", calling it the Hyperloop, in July 2012 at a PandoDaily event in Santa Monica, California.
  - The outline of the original Hyperloop concept was made public by the release of a **preliminary design** document in August 2013.
    - ☞ **Alpha-concept**. [Musk, Elon (August 12, 2013). "Hyperloop Alpha" (PDF). SpaceX. Retrieved August 13, 2013.]

Comparison to Hyperloop

- **Concorde**
  - Jet propulsion
  - Supersonic speed
  - Low air density
- **Railgun**
  - Guideway system
  - Magnetic propulsion
- **Air hockey table**
  - Air bearing



Concorde

Air hockey table:

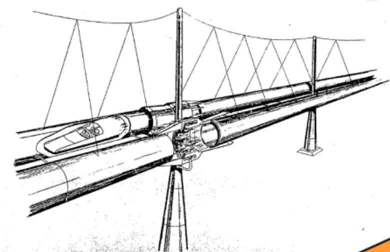
Railgun

Historical Review

Mass Transportation

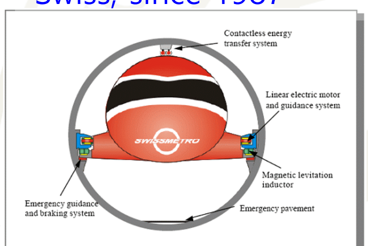
-Train like system

FRA Basic Research on **Tube-Vehicle System**
U.S.A, 1966-1969



TVS
Preliminary studies for various concepts

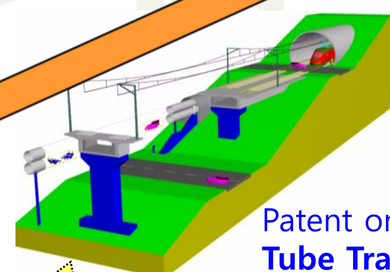
SWISSMETRO project
Swiss, since 1987



SWISSMETRO
Inter-city mass transportation
Speed: 400-700km/h
Vacuum level: 0.1 atm
Tube dia.: 5m

SWJTU plan
High-temperature Maglev
Speed: 600km~1000km/h
Vacuum level: 1335pa
Thrust: HTS

SWJTU long term plan
China. since 2005

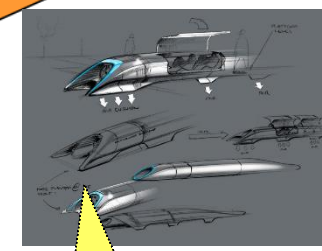


Patent on **Evacuated Tube Transportation**
U.S.A., 1997

ET3
Ultra high-speed Individual transportation
Speed: 320~6400km/h
Tube dia.: 1.5m
Thrust: LSM

Tube Train by KRRI
Super-speed HST connecting north-east Asian cities.
Speed: 700km/h
Thrust: LSM

Core technology development on **Super-speed Tube Train**
Korea, 2009-2011

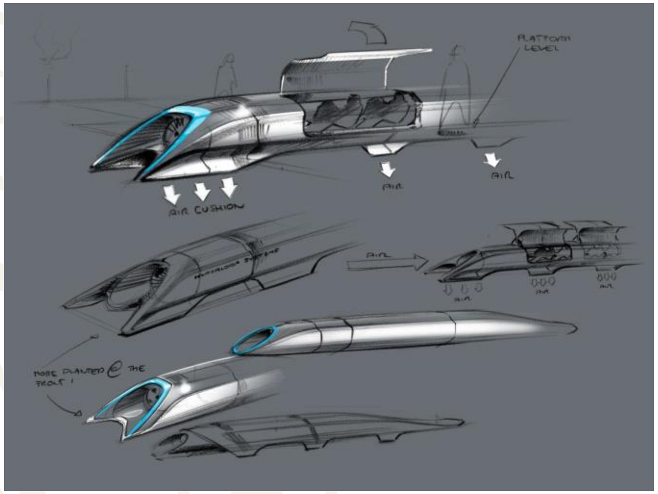


preliminary design on **Hyperloop**
U.S.A., 2013

Hyperloop
Alternative to California HST projcet
Speed: 1,200km/h
Vacuum level: 100Pa
Thrust: compressor
Levitation: air bearing

Individual Transportation

- Automobile like system



Hyperloop and Aerodynamics

HYPERLOOP-ALPHA
: THE ORIGINAL CONCEPT

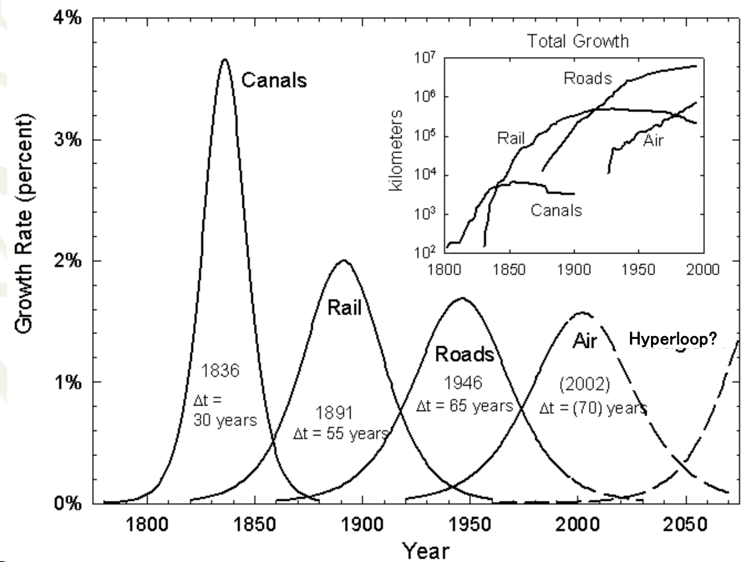
Alpha-concept : Motivation

- **California high speed rail**
  - Length: 1,300+ km
  - Speed: 350 km/h
  - Open: yr 2022
  - Route: San Francisco - Los Angeles
    - Silicon Valley, NASA JPL

- **Disappointment to California "high speed" rail**
  - **too expensive** and
  - **too slow**
    - to be an alternative to flying or driving
  - In addition, **less safe** by two orders of magnitude than flying

Alpha-concept : Requirements

- **Requirements of New transportation system:**
  - **Safer**
  - **Faster**
  - Lower **cost**
  - More **convenient**
  - Immune to **weather**
  - Sustainably **self-powering**
  - Resistant to **Earthquakes**
  - Not **disruptive** to those along the route



[J. H. Ausubel, C. Marchetti, P. Meyer, "Toward green mobility: the evolution of transport," *European Review*, Vol. 6, No. 2, 137-156 (1998).]

- **Fifth mode after boat^{1st} , trains^{2nd}, cars^{3rd}, planes^{4th}.**
  - Robert Goddard, Rand Corporation, ET3

Alpha-concept : Constraints

- **Transportation solution for high traffic city pairs?**
  - Range under 1,500km? ☞ Hyperloop
  - Range over 1,500km? ☞ Supersonic flight

- **Potential of Supersonic flight**
  - Being faster and cheaper
  - If noise problem is solved supersonic flight change game!

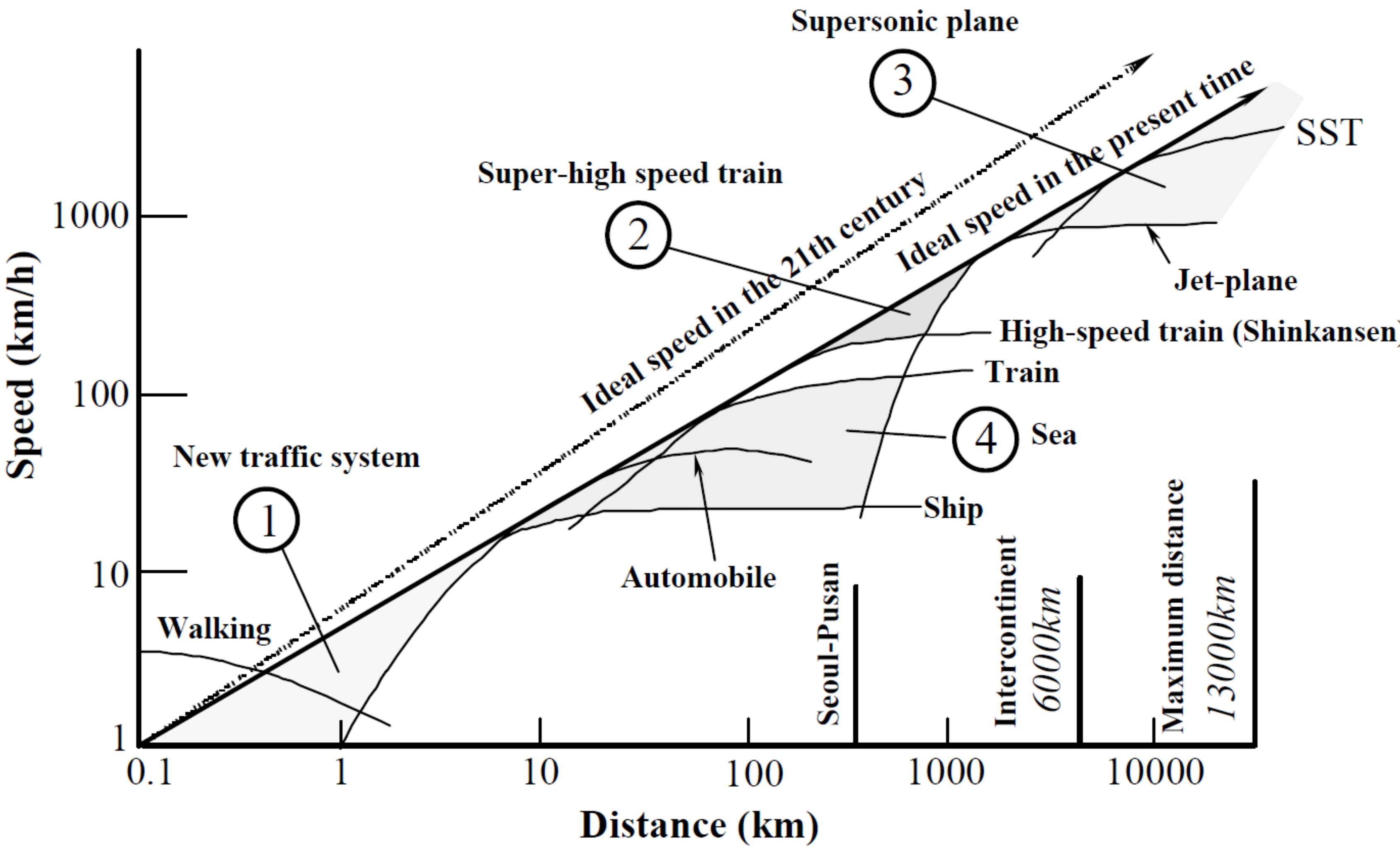
Lockheed Martin's supersonic concept

Boeing's advanced design concept

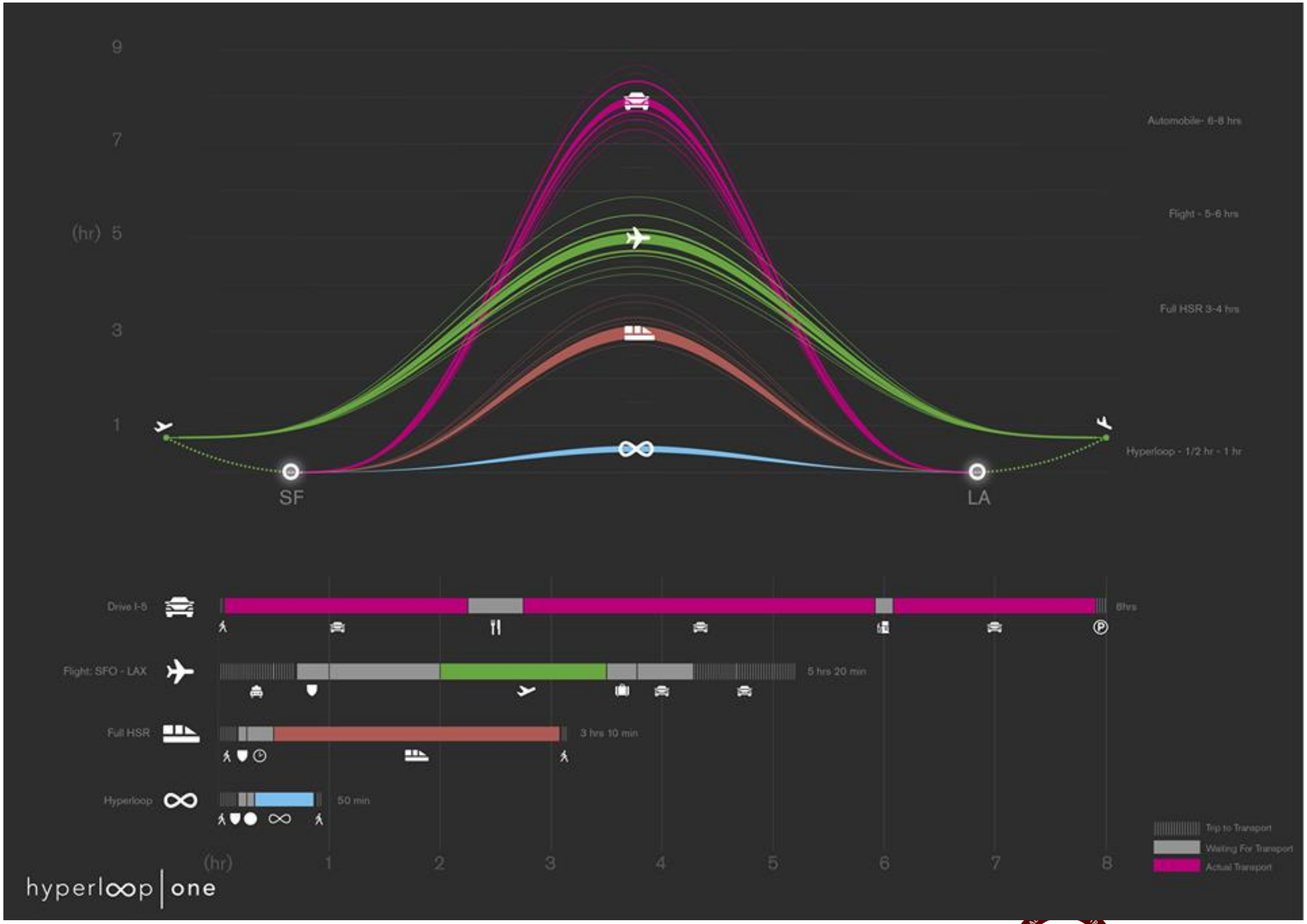
Northrop Grumman's concept

Lockheed Martin's advanced vehicle concept

Ref. Bouladon's Hierarchy

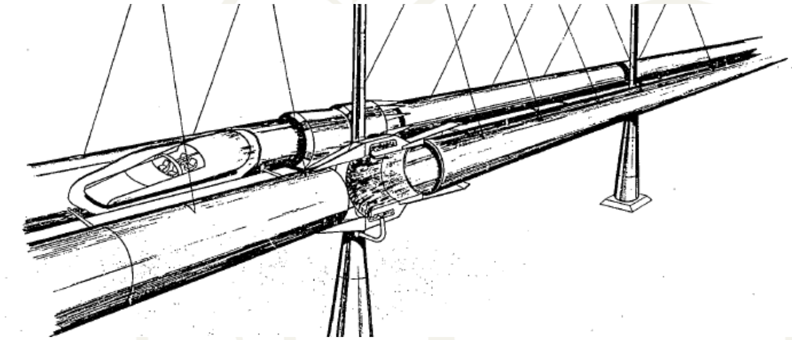


Ref. Comparison of trip time



Alpha-concept : Way of super fast travel

- **Enlarged version of the old pneumatic tubes**
  - Use very powerful fans to push air at high speed
  - Friction of the air column at sonic velocity is too much



ITTRI Fluid-entrained Vehicle System

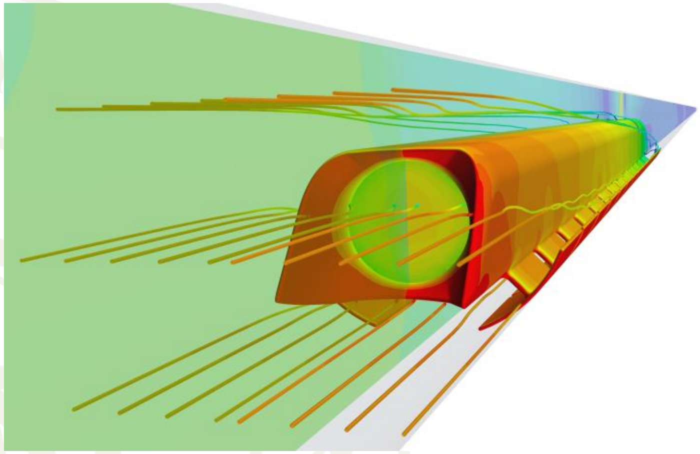
- **Vacuum in the tube with electromagnetic suspension**
  - Incredibly hard to maintain a near vacuum in tube
  - Standard commercial pumps can handle(overcome) the air leak
    - In Swissmetro project, it means about 0.1 atm
    - In Hyperloop-alpha concept, it means about 0.001 atm

Alpha-concept : Kantrowitz Limit

- **Kantrowitz limit**
  - Nature's top speed law for a given tube to pod area ratio
    - Over the speed, the flow choke!
  - Two solutions to Kantrowitz limit;
    - Go slowly
    - Go really, really fast ☞ *g* loads problem
- **Solution: Electric compressor fan on the nose of the pod**
  - **Overcome the Kantrowitz limit**
    - Actively transfer high pressure air from the front to the rear
  - Create a **low friction** suspension system
    - Air bearing have been demonstrated to work at speeds of Mach 1.1 with very low friction
  - Self-powering is able ☞ Battery capacity is enough
  - External linear electric motor: every 70 miles (1% of the tube length)

Alpha-concept : Technical specifications

- **Major system parameters**
  - Length of route 350 mile (=560 km)
  - Total trip time: 35 min (=600 mph schedule speed)
  - Maximum speed: 760 mph (=1,200 km/h)
  - Headway: 2 min (=30 caps in overall system)
    - max. headway is 30 sec & 40 capsules at rush hour
  - Unit capacity: 28 person/capsule
  - System capacity: 7.4 mil person/line/year
    - Assuming 24hr operation with 2min interval
  - Total power: 21 MW/system
    - Compressors 13 MW/system
    - Propulsion motor & Vacuum pump
    - Aerodynamic drag 4 MW/system (! is included to compressor and propulsion motor)
  - Total cost: 6 bill USD
    - Corresponds to 20 USD per ticket under 20yr Amortizing



Hyperloop and Aerodynamics

AERODYNAMIC CHARACTERISTICS

Definitions

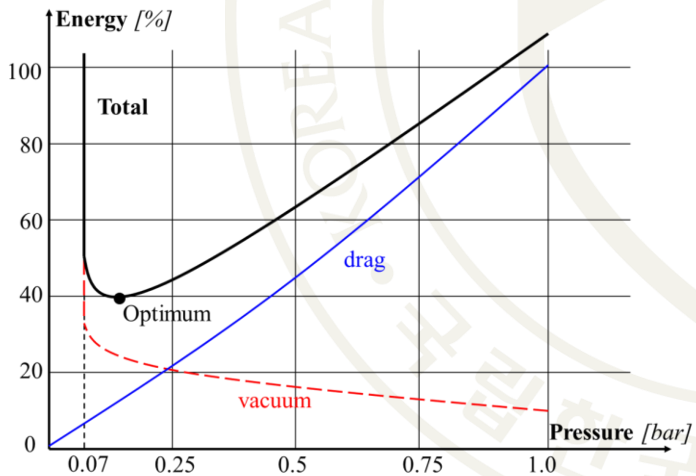
- **Sonic Tube Transportation System**
  - a transportation system using **evacuated tube** as transportation mode and with vehicles running at about **sonic speed**

- **Hyperloop**
  - A kind of sonic tube transportation system, employing

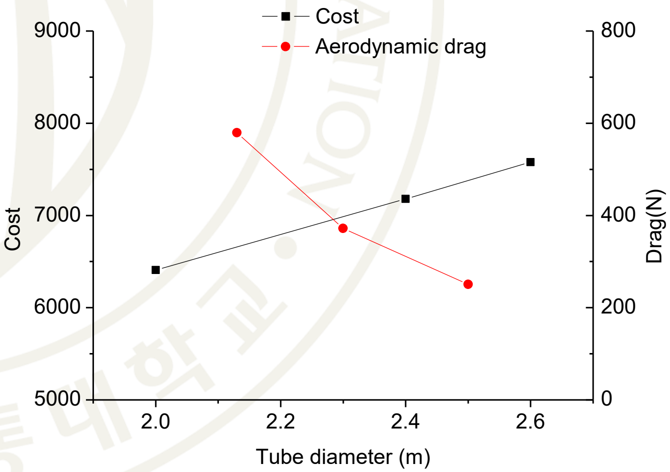
1. **Compressor** mounted on the nose of the vehicle to overcome Kantrowiz limit and to enable self-powering
2. **Air-bearing** for suspension system for simple infrastructure

Role of aerodynamics

- **The original idea comes from aerodynamics**
  - Reducing aerodynamic drag by decreasing air density $D = \frac{1}{2}\rho U^2 S C_D$
- **Determines governing system parameters**
  - Tube diameter, vacuum level at a given capsule speed
- **Interfaces with almost subsystems**
  - Traction, levitation, vehicle stability, evacuation pump, system safety…



Determination of optimum evacuation level



Determination of optimum tube diameter

Fluid characteristics by fluid numbers

- **Knudsen number**

$$\mathbf{Kn} = \frac{\lambda}{L} = \sqrt{\frac{\Upsilon\pi}{2}}\cdot\frac{M}{Re} = \sqrt{\frac{1.4\times3.14}{2}}\times\frac{0.91}{45{,}983} = 2.95\times10^{-5}$$

☞ Continuum flow

- **Mach number**

$$\mathbf{M} = \frac{U}{c} = \frac{U}{\sqrt{\gamma RT}} = \frac{313.89\ m/s}{\sqrt{1.4\times287.058\ J\cdot kg^{-1}\cdot K^{-1}\times293.15\ K}} = 0.91$$

☞ Compressible and Transonic flow

- **Reynolds number**

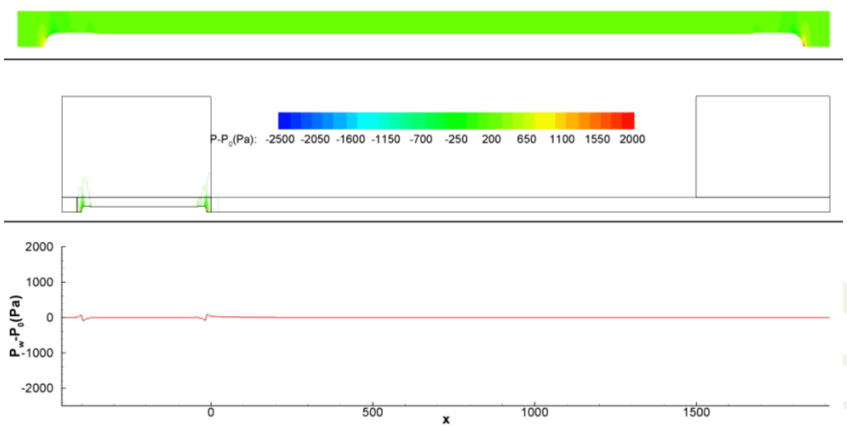
$$\mathbf{Re} = \frac{\rho UL}{\mu} = \frac{0.00119kg/m^3\times313.89\ m/s\times2.23m}{1.81\times10^{-5}Pa\cdot s} = 45{,}983$$

☞ Low Reynolds number flow

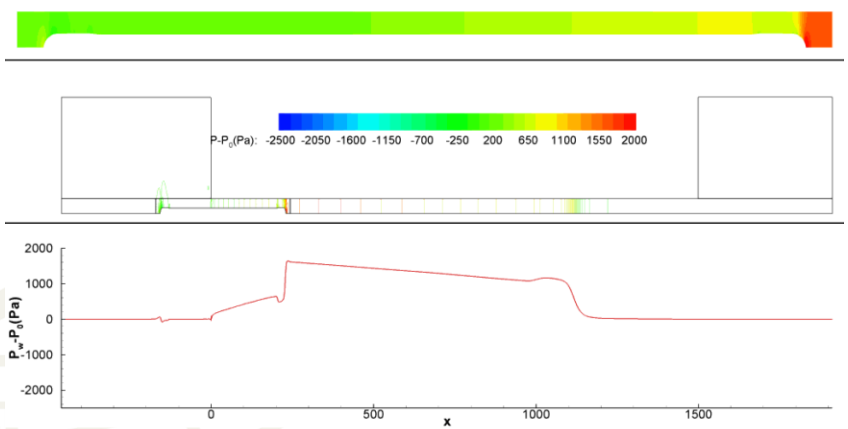
- **Kantrowiz limit**
  - For M=0.91, $\frac{A_{bypass}}{A_{tube}} = \left[\frac{\gamma-1}{\gamma+1}\right]^{\frac{1}{2}}\left[\frac{2\gamma}{\gamma+1}\right]^{\frac{1}{\gamma-1}}\left[1+\frac{2}{\gamma-1}\frac{1}{M^2}\right]^{\frac{1}{2}}\left[1-\frac{\gamma-1}{2\gamma}\frac{1}{M^2}\right]^{\frac{1}{\gamma-1}} = 0.99$
  - For BR=0.36, corresponding M=0.595 ☞ Chocked flow

Characteristics of internal and external flow

- **External flow characteristics**
  - Flow disturbances induced by the motion of vehicle
  - Aerodynamic forces are exerted on the vehicle
- **Internal flow characteristics**
  - Flow disturbances are enhanced by the tube boundary
  - Linear propagation of flow disturbance



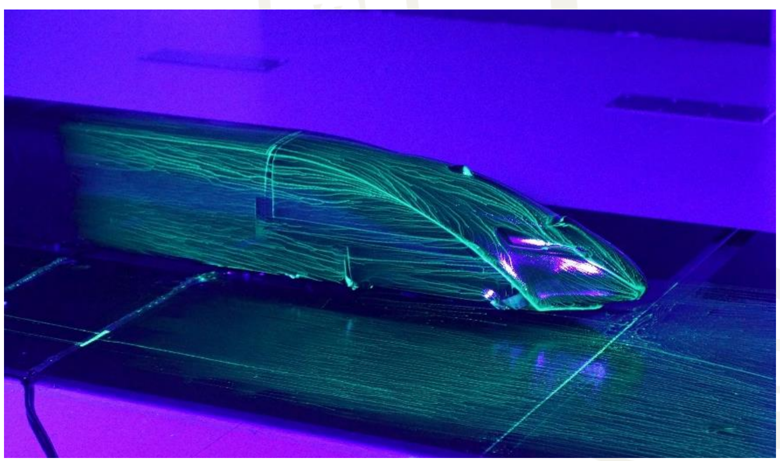
Before tunnel entry

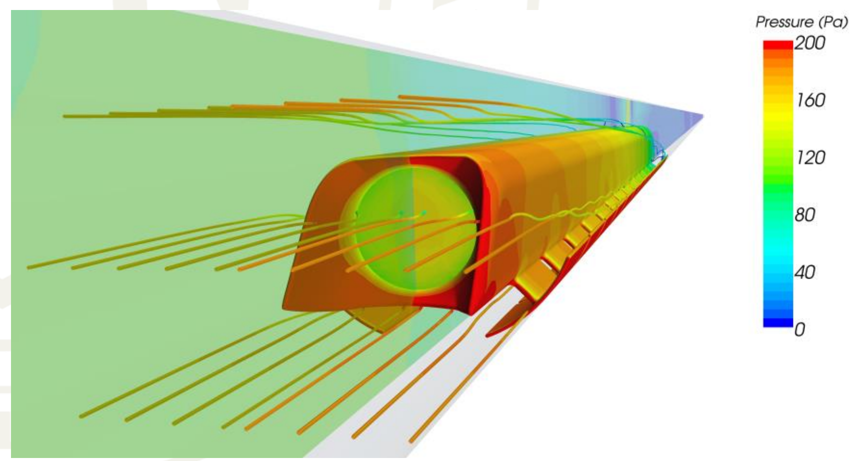


After tunnel entry

Methods of investigation

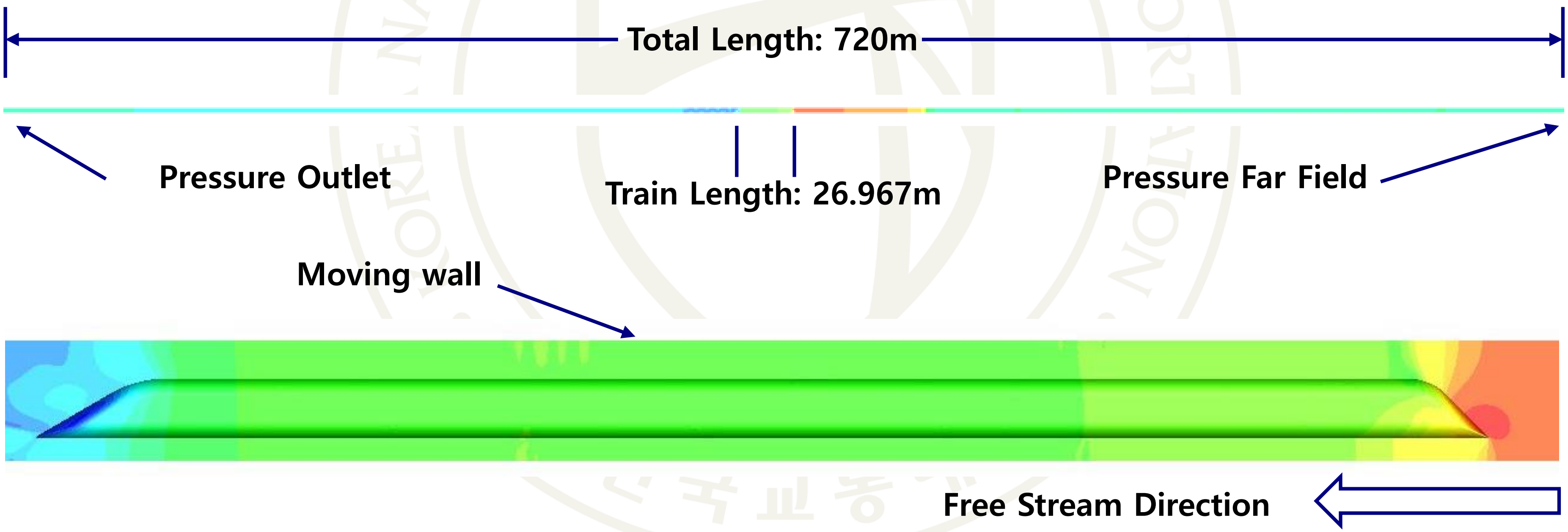
- **Wind tunnel test**
  - Unable to represent the relative motion between tube and capsule
  - Hard to fulfill the extreme flow conditions (Mach #, Reynolds #)
- **Computational Fluid Dynamics**
  - Easy to represent the relative motion between tube and capsule as well as to give the extreme flow conditions
  - Hard to determine the boundary conditions



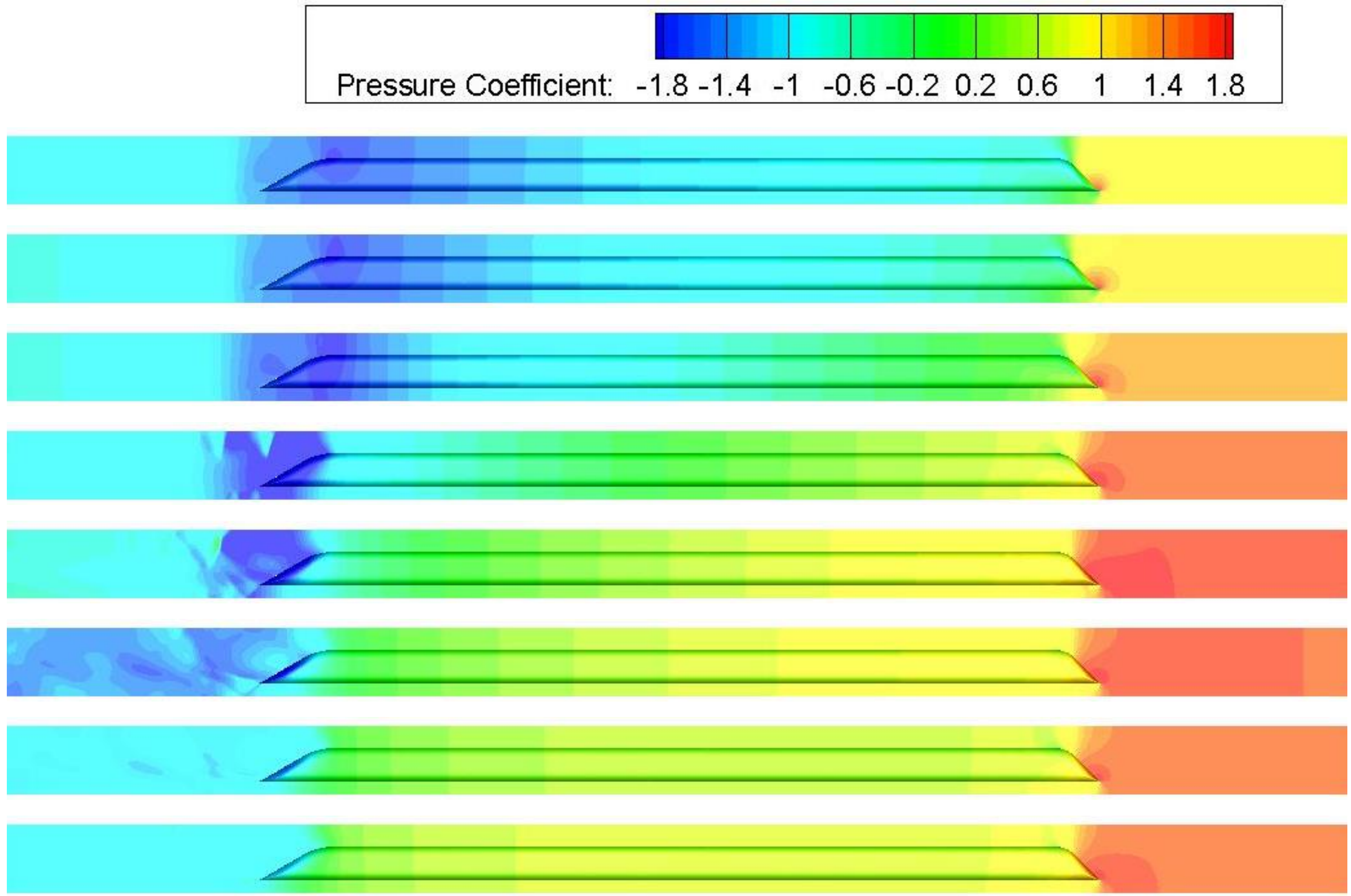


CFD study <1> - w/o Compressor

- **Governing equation**
  - 3D steady compressible Navier-Stokes equation
- **Turbulence model**
  - k-ω SST turbulence modeling
- **Boundary conditions**



Result – w/o Compressor <1/3>



Mach=0.3 (103 m/s)

Mach=0.4 (137 m/s)

Mach=0.5 (172 m/s)

Mach=0.6 (206 m/s)

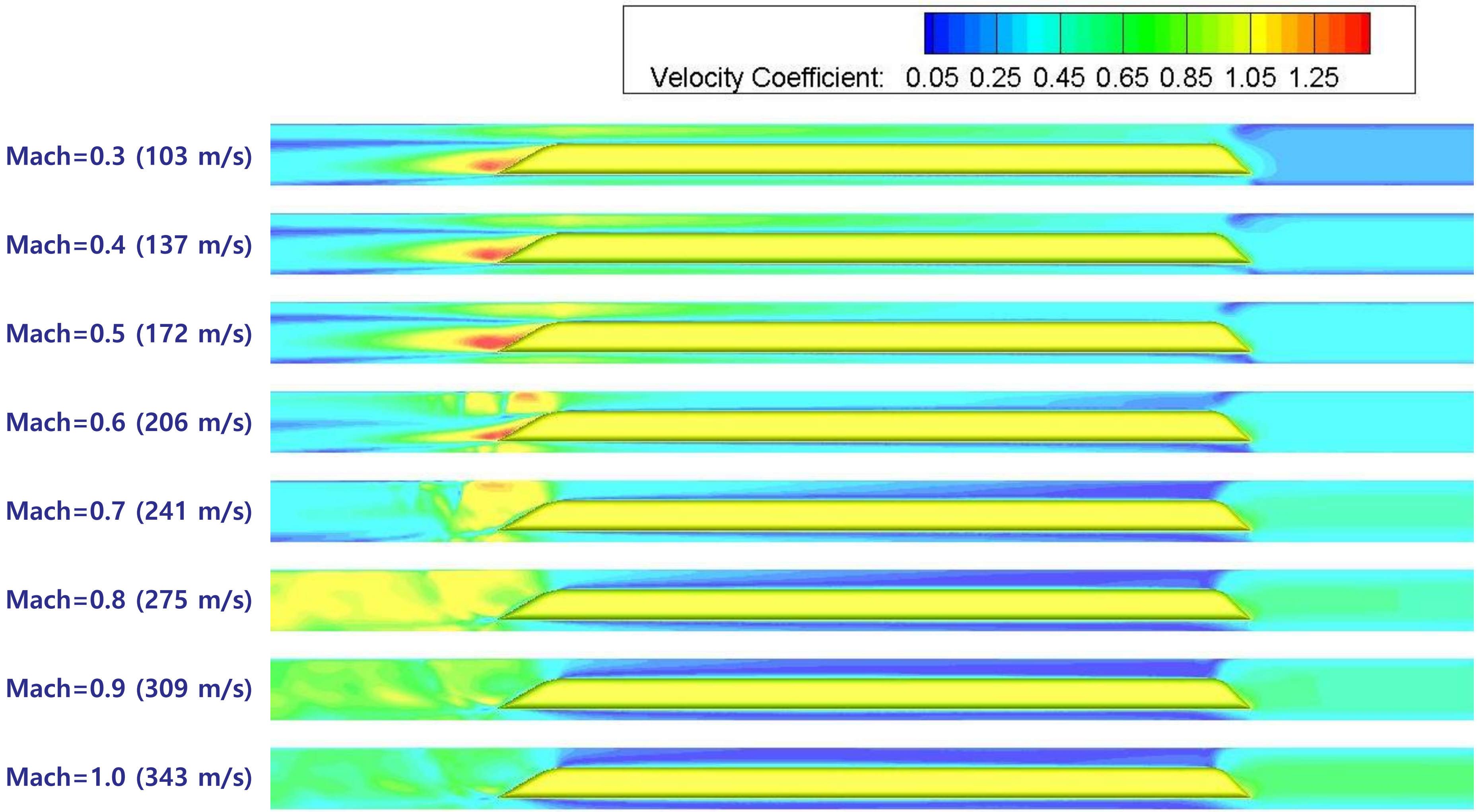
Mach=0.7 (241 m/s)

Mach=0.8 (275 m/s)

Mach=0.9 (309 m/s)

Mach=1.0 (343 m/s)

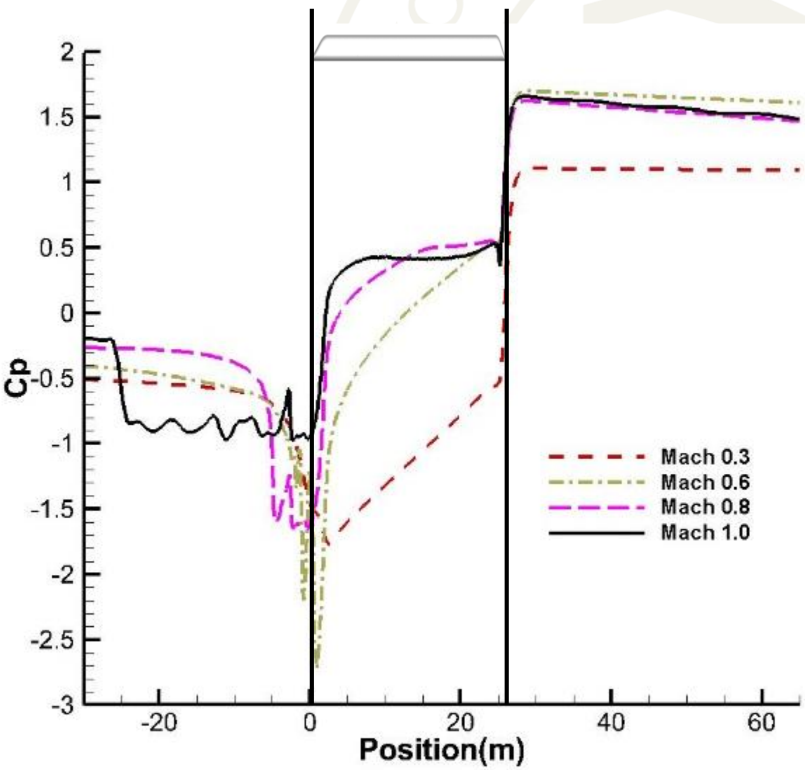
Result – w/o Compressor <2/3>

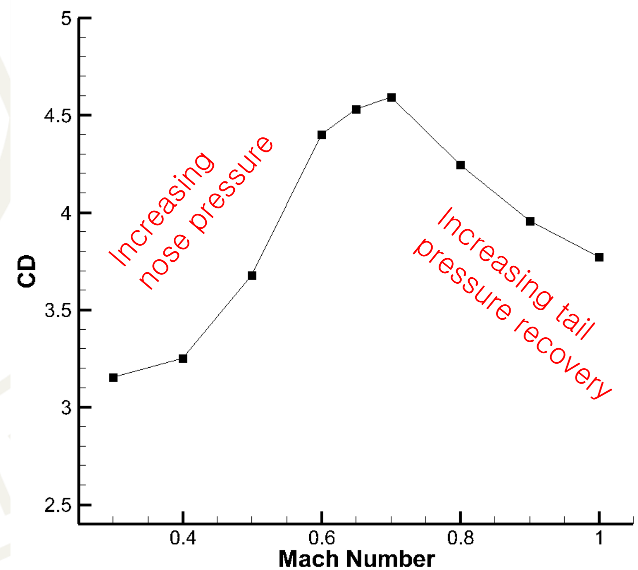


Result – w/o Compressor <3/3>

- **Drag coefficient**
  - Maximum at Mach number=0.6~0.7
  - $C_{D,vis}$ decrease according to Mach number

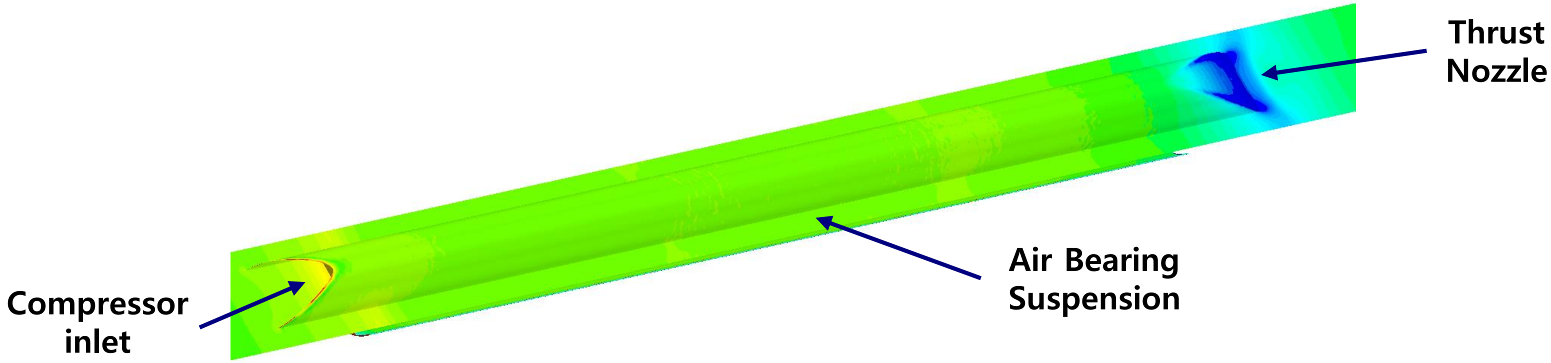
Mach	Cd_vis	Cd_pre	Cd_tot
0.30	2.0384	1.1143	3.1526
0.40	2.2346	1.0169	3.2515
0.50	2.7456	0.9306	3.6762
0.60	3.5840	0.8145	4.3985
0.65	3.7650	0.7739	4.5389
0.70	3.8509	0.7397	4.5905
0.80	3.5772	0.6692	4.2464
0.90	3.3348	0.6215	3.9562
1.00	3.1796	0.5903	3.7699





CFD study <2> - with Compressor

- **Governing equation**
  - 3D steady compressible Navier-Stokes' equation
- **Turbulence model**
  - k-ω SST turbulence modeling
- **Boundary conditions**
  - Compressor inlet : mass flow inlet condition with 0.49kg/s
  - Thrust nozzle : mass flow outlet condition with 0.29kg/s
  - Air bearing suspension: mass flow outlet condition with 0.20kg/s



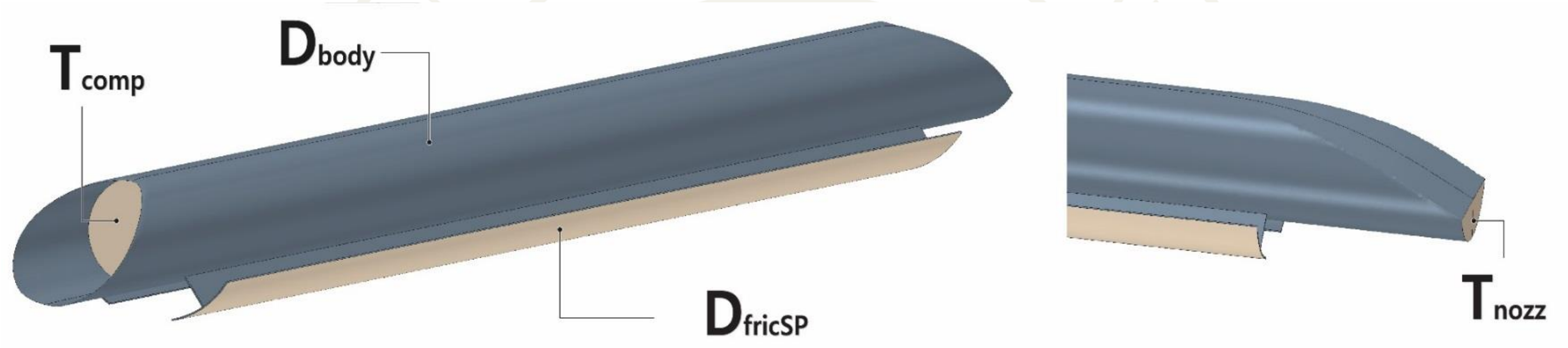
Boundary conditions

※ Hyperloop Alpha

	Inner Tube	① Compressor Inlet	② Air Bearing	③ Thrust Nozzle	Etc.
Temperature	293.2 K	293.2 K	400 K	300 K	
Pressure	100 Pa	*100 Pa*	7,500 Pa	100 Pa	
Mass Flow Rate	-	0.49 kg/s	0.2 kg/s	0.29 kg/s	① = ② + ③
Flow Velocity	-	310.48 m/s	0.08 m/s	586.21 m/s	From Mass Flow Rate
Air Density	0.00119kg/m^3	*0.00119kg/m^3*	0.06536kg/m^3	0.00116kg/m^3	From Equation of State
Area	3.91 m^2	1.33 m^2	37.80 m^2	0.43 m^2	
Drag	-	150 N	-	170 N	320 N in Hyperloop Alpha
Lift(Gravity)	-	-	147,000 N	-	Total Weight: 15,000kg

Forces exerted on the body

- **Computation of crucial aerodynamic performance**
  - Performance of compressor, air bearing suspension, thrust of nozzle, drag of capsule, etc.



$$\sum F_x = \sum D - \sum T$$

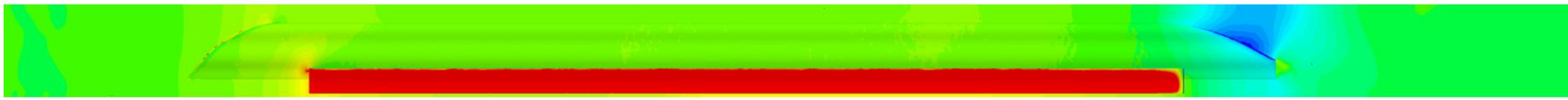
$$\sum D = D_{body} + D_{fricSP}$$

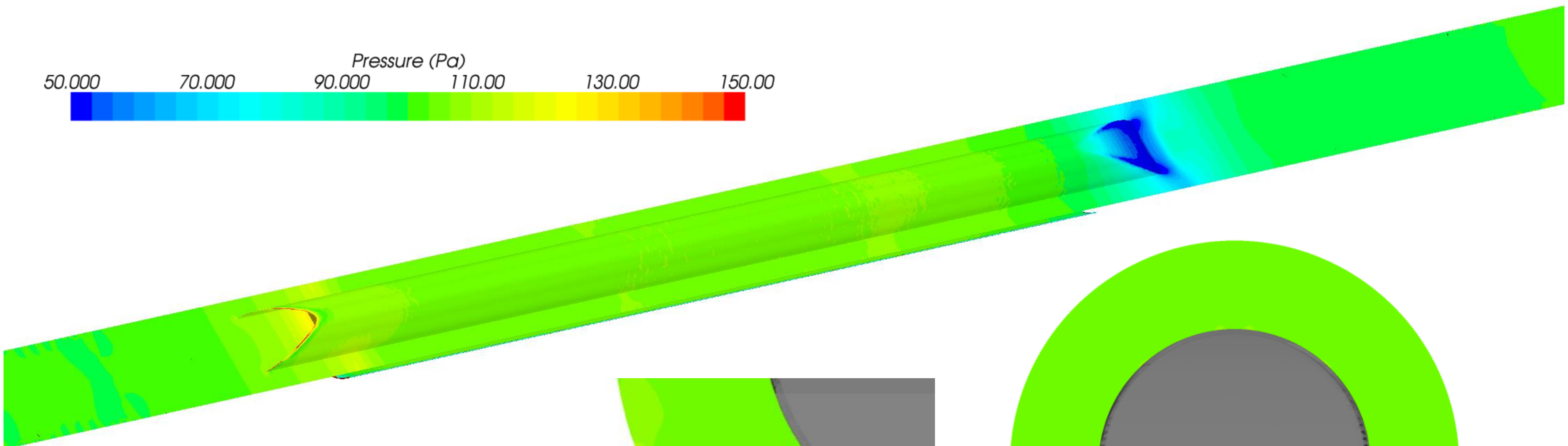
$$\sum T = T_{comp} + T_{nozz} = \dot{m}_{comp} v_{comp} + \dot{m}_{nozz} v_{nozz}$$

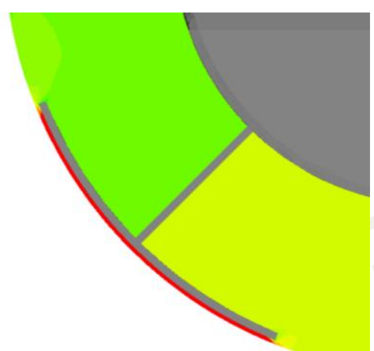
Cruise Condition

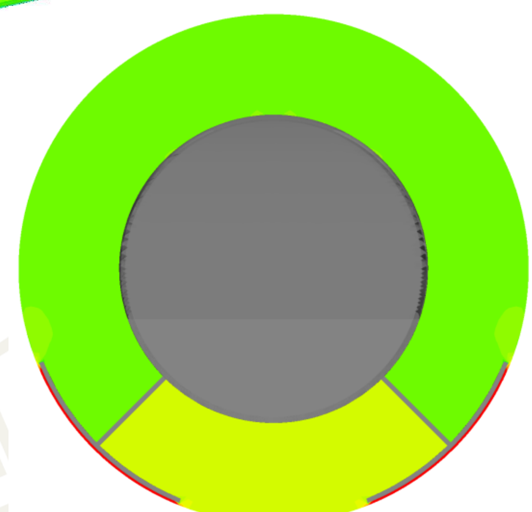
$$\sum D = \sum T$$

Result – with Compressor <1/2>



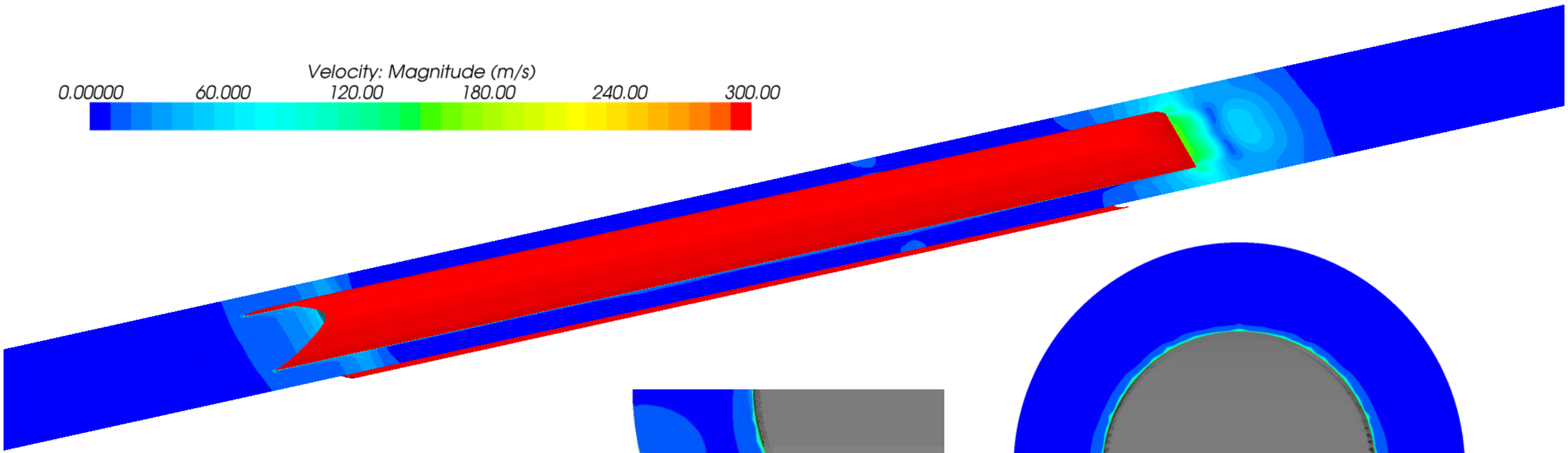


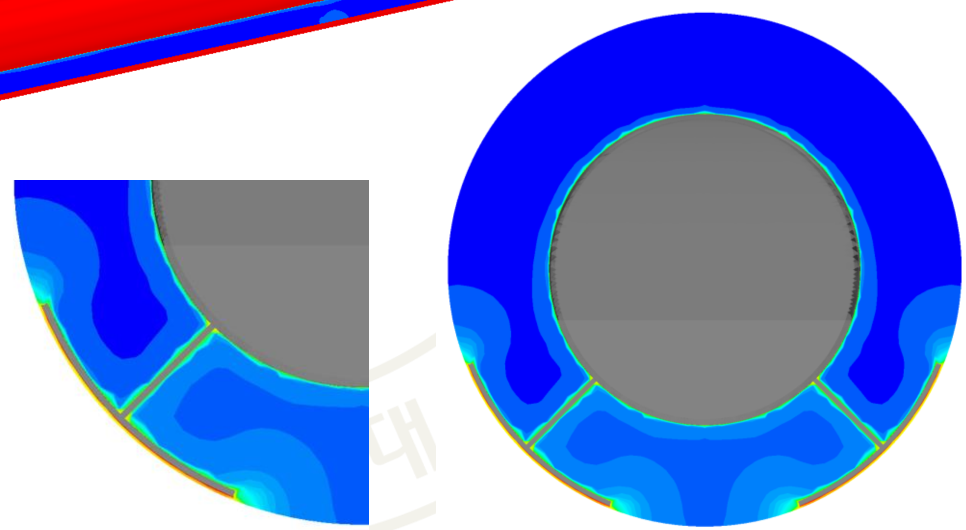




Pressure distribution
inside the tube

Result – with Compressor <2/2>





Velocity distribution inside the tube

Result – with Compressor <3/3>

- **Thrust**
  - Calculated thrust at compressor(133) is smaller than expected(150)
  - Calculated thrust at nozzle(172) is almost the same with the alpha document(172)
- **Drag**
  - Calculated capsule drag(190) is almost the same with alpha(190)
  - Air bearing friction drag has not been considered

	Thrust			**Drag**		
	Compressor (T_{comp})	**Nozzle** (T_{nozz})	**Sum** ($\sum T$)	**Capsule** (D_{body})	**Air bearing** (D_{fricSP})	**Sum** ($\sum D$)
Hyperloop Alpha	≈ 150	**170**	**≈ 320**	**191**	129	**320**
Analysis	133	**172**	**305**	**190**	-	**190**

Conclusions

- **Aerodynamics plays a central role in the Hyperloop system**
- **The flow of Hyperloop system is very unique and complicated**
- **CFD study w/o compressor**
  - Weak bypass flow and strong pressure recovery over Kantrowiz limit speed. => decrease of drag coefficient
  - Increase of mass flow rate to train direction => mass accumulation in finite length tube
- **CFD study with compressor**
  - Validation of compressor performance on nozzle thrust and aerodynamic drag for Hyperloop-alpha model