FAA CENTER OF EXCELLENCE FOR ALTERNATIVE JET FUELS & ENVIRONMENT

Acoustical Model of Mach Cut-Off Flight

Project 42

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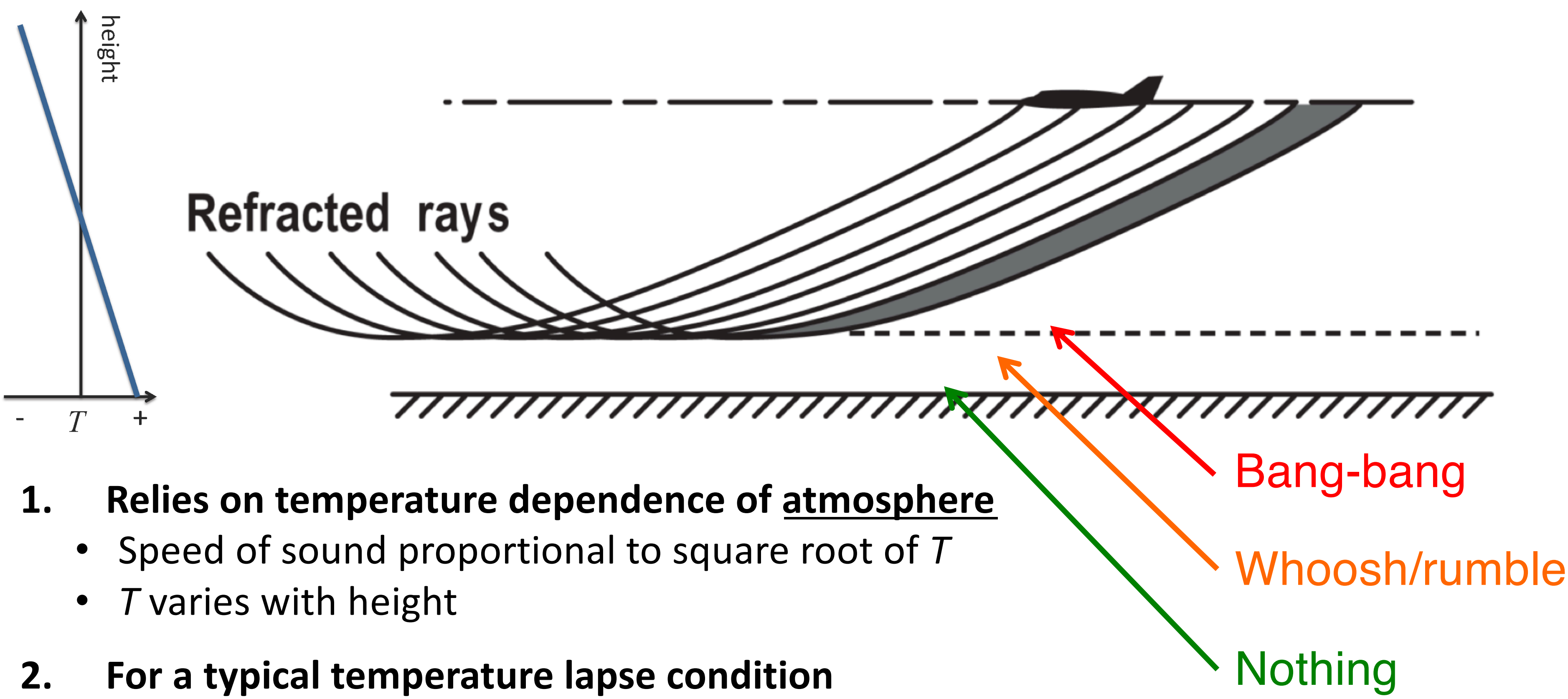
Mach cut-off occurs when the aircraft flies supersonically without producing a sonic boom on the ground

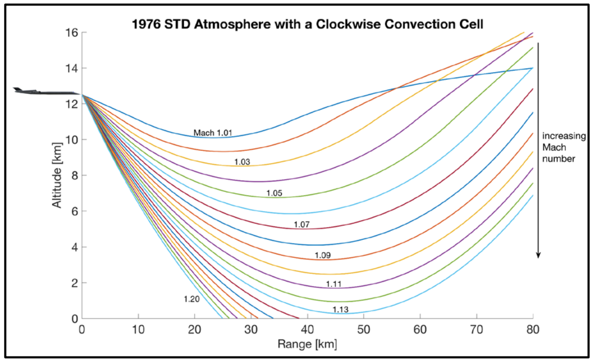


1. **Relies on temperature dependence of atmosphere**
   - Speed of sound proportional to square root of *T*
   - *T* varies with height
2. **For a typical temperature lapse condition**
   - Aircraft is supersonic at flight altitude, but not at ground
   - Rays refract upwards, so no boom on the ground
3. **What you hear depends on how close you are**

[4] HAGLUND, G., & KANE, E. (1973). Flight test measurements and analysis of sonic boom phenomena near the shock wave extremity. NASA Report CR-2167.

Project 42 research in 2019

- Prediction of how often Mach cut-off sounds would be heard
  - Advanced ray tracing
  - High-resolution weather data across U.S.



- Perceptual analysis of the new Mach cut-off sounds
  1. Descriptor study
  2. Factors of annoyance study
  3. **Degree of annoyance and relative preference study**

Approach for ray-tracing

- We want to predict the statistical occurrence of focus booms on the ground due to atmosphere.
- A 3-D ray-tracing algorithm was developed to predict the Mach cut-off operation
  - Includes effects of vertical winds
- Atmospheric data from the Climate Forecast System Version 2 (CFSv2) was used [Saha, 2014]
  - But not enough resolution
- Now using High-Resolution Rapid Refresh (HRRR) numerical weather model for atmosphere [Benjamin, 2016]
- Running many ray-tracing simulations combining different flight paths, flight altitudes, and atmospheres

Using HRRR for the atmosphere

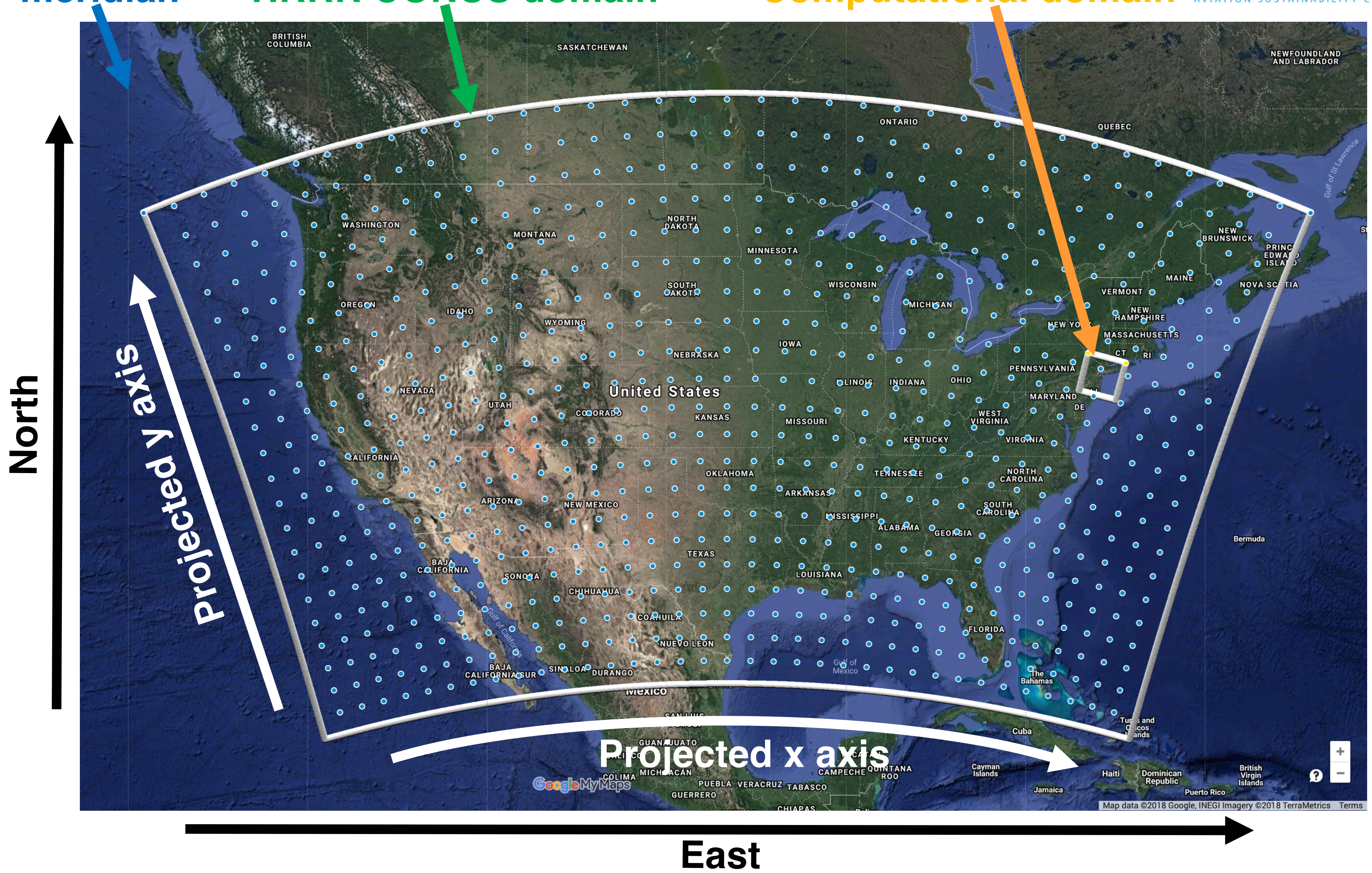
- High-Resolution Rapid Refresh model [Benjamin, 2016]
  - A numerical weather model developed by NOAA ESRL and is run operationally every hour at NCEP's Environmental Modeling Center
  - The operational HRRR generates hourly forecasts gridded at 3 km for 18 to 36 hours over the contiguous United States.
  - The highest spatial and temporal resolution forecast system run by NCEP
  - Contains surface and upper-level pressure fields for analyses and forecasts
  - The Lambert Conformal Conic Projection is used by NOAA for the HRRR data grid.
  - Archived HRRR data is available at the University of Utah’s Center for High Performance Computing [Blaylock, 2017]

Why choose HRRR?

- HRRR has much better spatial and temporal resolution.

Model	Domain	Grid Points or # of Stations	Grid Spacing	Vertical Levels	Pressure Top	Initialized
IGRA	Global	Nearly 1000 stations	--	50 ~ 82	--	12 hours
CFSv2	Global	720 x 361	0.5 degree/55 km	37	1 mbar	6 hours
HRRR	CONUS	1799 x 1059	3 km	40	50 mbar	Hourly

HRRR CONUS domain



meridian

HRRR CONUS domain

Computational domain

North

East

- CONUS domain includes 1799 X 1059 grid points, with 3 km horizontal spacing.
- Only 1 out of every 50 HRRR grid points is plotted along each axis.

Previous research

- G. Haglund and E. Kane, "Flight test measurements and analysis of sonic boom phenomena near the shock wave extremity," NASA Report CR-2167 (1973).
  - "The criterion for shock wave cutoff above the ground from a supersonic airplane is that the airplane ground speed must be less than the **maximum speed of propagation of the shock wave** beneath the airplane."

G. Haglund and E. Kane (1973)

- Threshold Mach number (M_T)
  - The maximum airplane Mach number for which complete shock wave refraction can occur at or above the ground.

$$M_T = \frac{1}{a_o}\{[a(Z) - u_n(Z)]_{\max} + u_{n_o}\}$$

where

M_T = threshold Mach number

Z = altitude

$a(Z)$ = speed of sound at altitude Z

$u_n(Z)$ = wind component at altitude Z parallel to flight path (tailwind is negative)

$[a(Z) - u_n(Z)]_{\max}$ = maximum shock propagation speed between the airplane and the ground in the direction of flight

a_o = sound speed at airplane

u_{no} = wind speed at airplane (tailwind is negative)

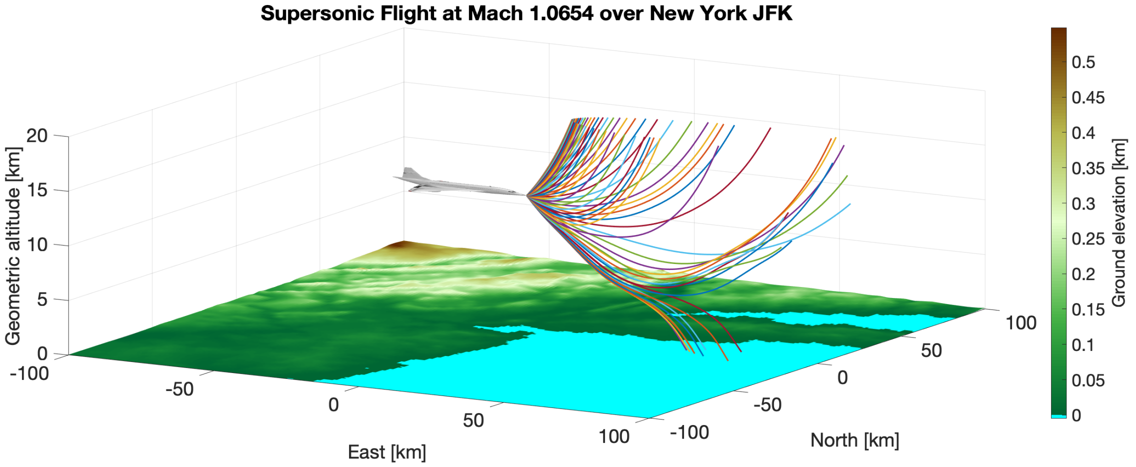
Impact of effective sound speed along flight direction on Mach cut-off flight

- An example: eastbound flight over JFK at a flight altitude of 12.5 km

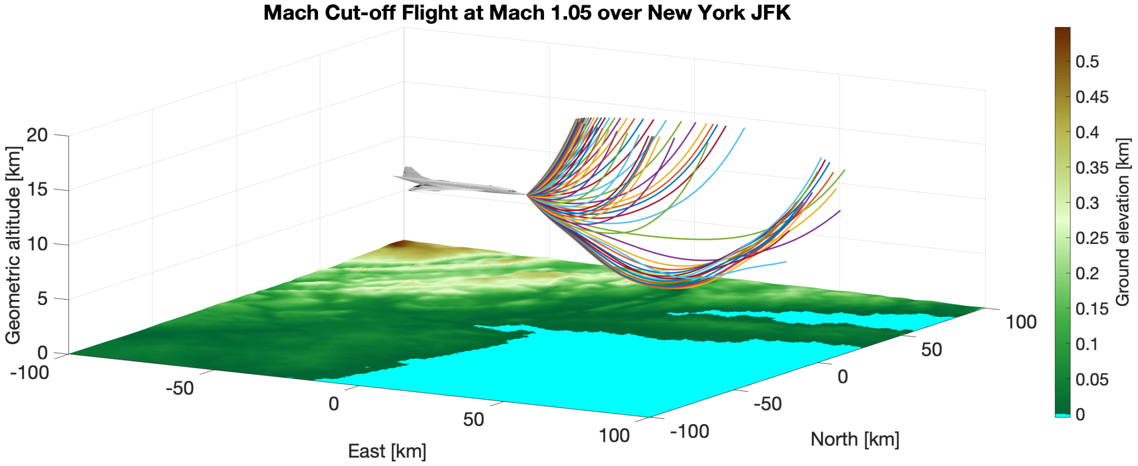
Atmospheric and flight variables	Jan 01 2017 12 AM UTC (8 PM EDT)	Jan 01 2017 6 AM UTC (2 AM EDT)	Jan 01 2017 12 PM UTC (8 AM EDT)	Jan 01 2017 6 PM UTC (2 PM EDT)
From atmospheric data				
Threshold Mach number from Haglund and Kane's formula	1.0076	1.0271	1.0752	1.0654
Maximum effective sound speed along flight direction	801.53 mph	810.56 mph	834.91 mph	815.58 mph
Altitude of maximum effective sound speed along flight direction	10.[illegible] km	9.7[illegible] km	8.0[illegible] km	5.0[illegible] km
[illegible]om ray-tracing s[illegible]ulations				
Cut-off Mach number from ray tracing	1[illegible]0	1[illegible]2	1[illegible]6	1[illegible]5
Maximum aircraft ground speed from ray tracing	796.[illegible] mph	805.[illegible] mph	825.[illegible] mph	805.5[illegible] mph
Altitude of caustic from ray tracing	12.50 km	10.95 km	8.57 km	5.49 km

Accuracy of Haglund and Kane's formula

- An example: eastbound flight over JFK at a flight altitude of 12.5 km at 2 PM EDT, Jan 1, 2017
  - From Haglund and Kane's formula, $M_T = 1.0654$, under which the rays will reach the ground.



  - Based on ray-tracing calculations, $M_c = 1.05$, under which the rays will not reach the ground.



Statistical Analysis of Ray-tracing Simulations

Cases:

- Times: 12AM UTC (8PM EDT), 6AM UTC (2AM EDT),
  12PM UTC (8AM EDT), 6PM UTC (2PM EDT)
- Days: Jan 1, Apr 1, Jul 1, Oct 1 in 2017
- Flight altitudes: 41,000 ft and 50,000 ft
- Assumptions: we look at Mach numbers every 0.01 of a Mach and we assume the caustic must be at least 500 m above the ground.

Number of Cases for Mach Cut-off Study for 2017

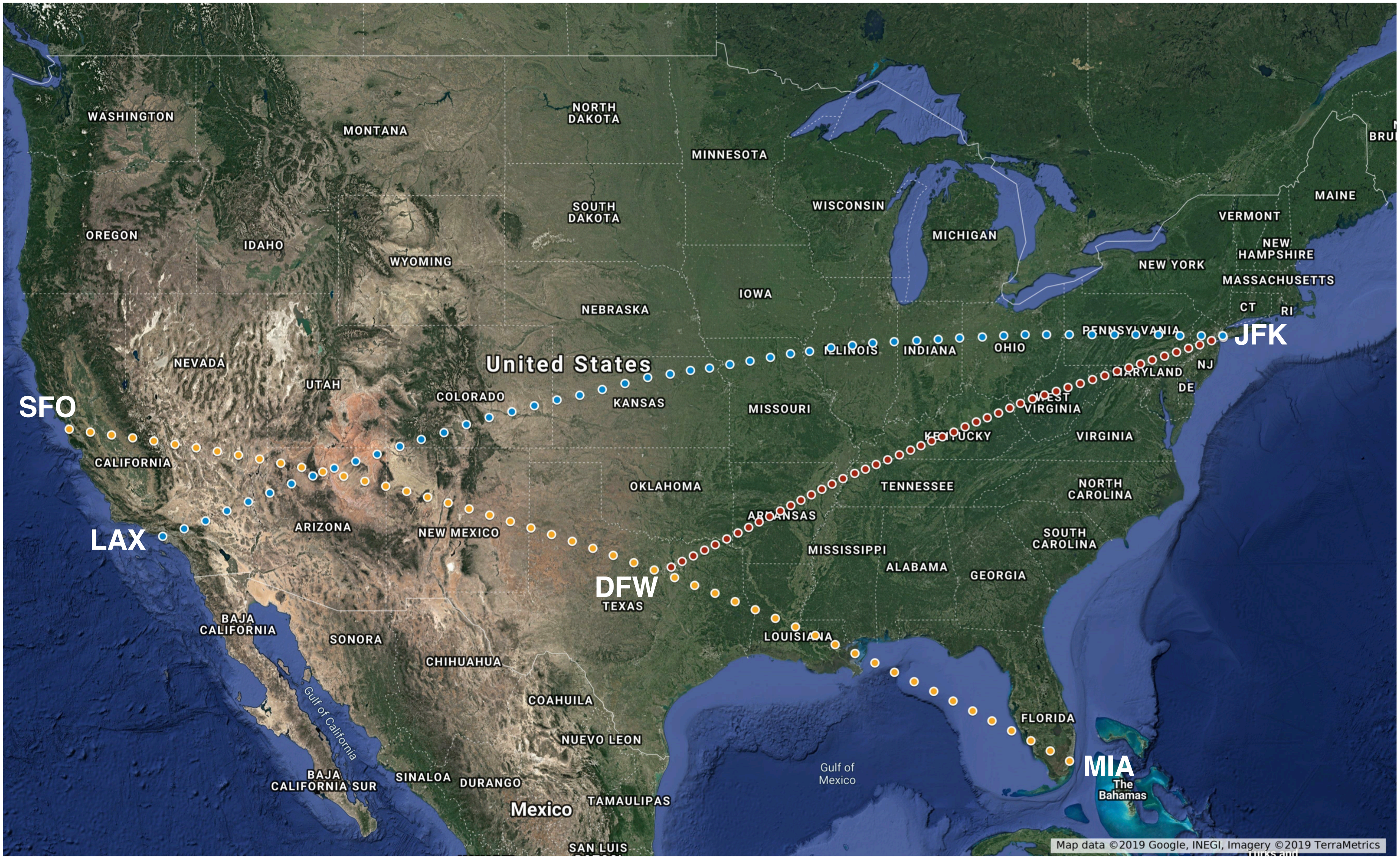
	Number of simulations
Times per day	4
Days per year	4
Flight altitude	2
Locations per air route	50
Air routes	3
Round-trip	2
Total	9600

Analysis:

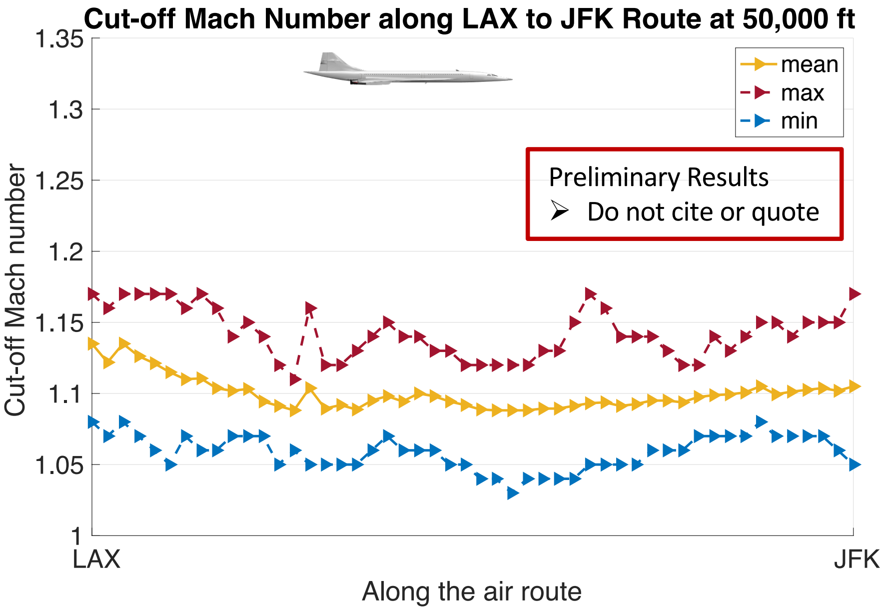
- For each aircraft altitude and location along a route, the mean, maximum and minimum cut-off Mach number and ground speed will be calculated over 16 weather conditions in 2017.

Air routes for Mach cut-off study

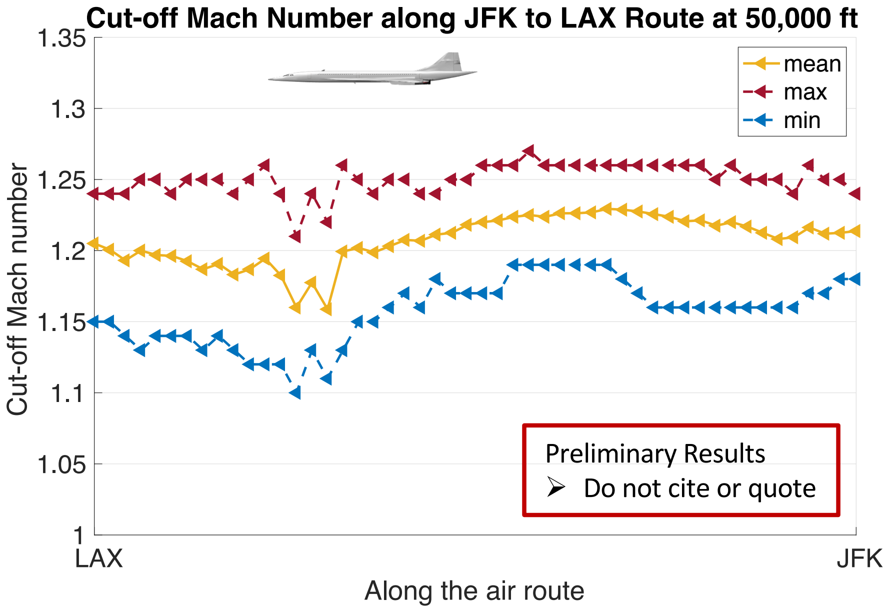
- LAX–JFK (completed), SFO–MIA (completed), and DFW–JFK (underway)



Cut-off Mach number for LAX-JFK route in 2017


Cut-off Mach Number along LAX to JFK Route at 50,000 ft

Preliminary Results
➢ Do not cite or quote


Cut-off Mach Number along JFK to LAX Route at 50,000 ft

Preliminary Results
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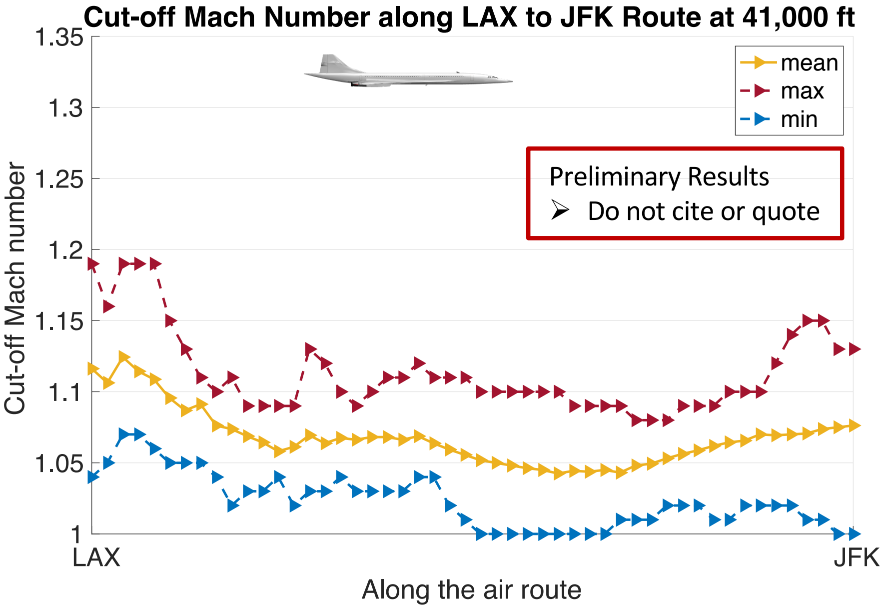
Cut-off Mach Number along LAX to JFK Route at 41,000 ft

Preliminary Results
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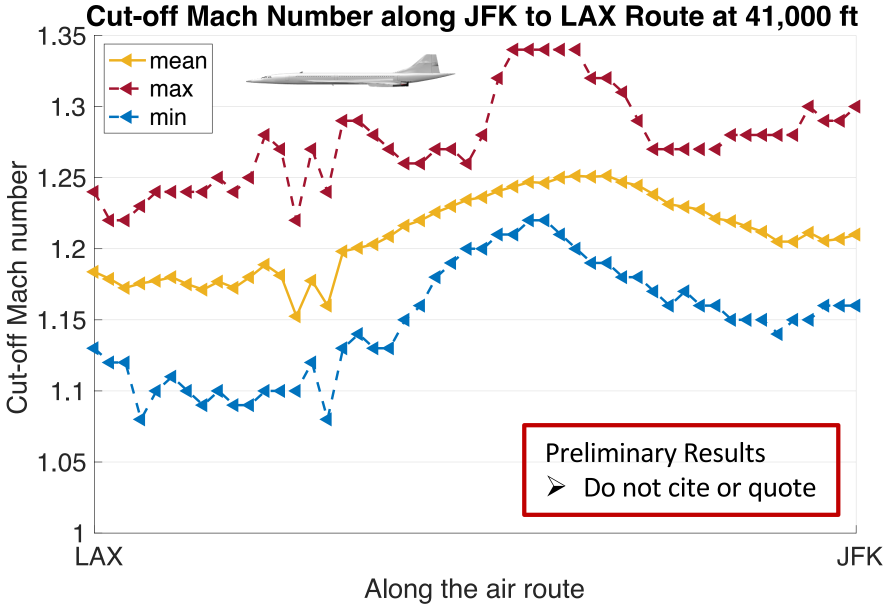
Cut-off Mach Number along JFK to LAX Route at 41,000 ft

Preliminary Results
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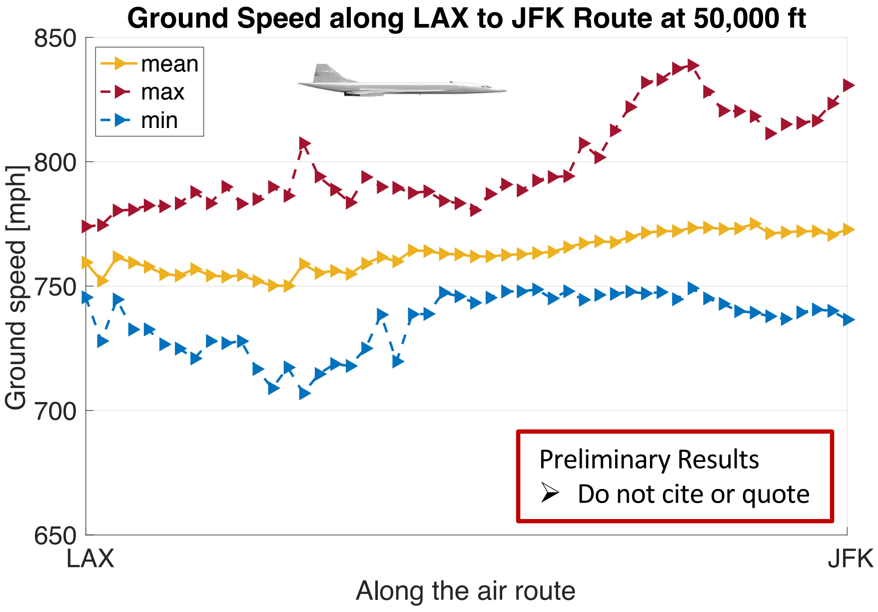
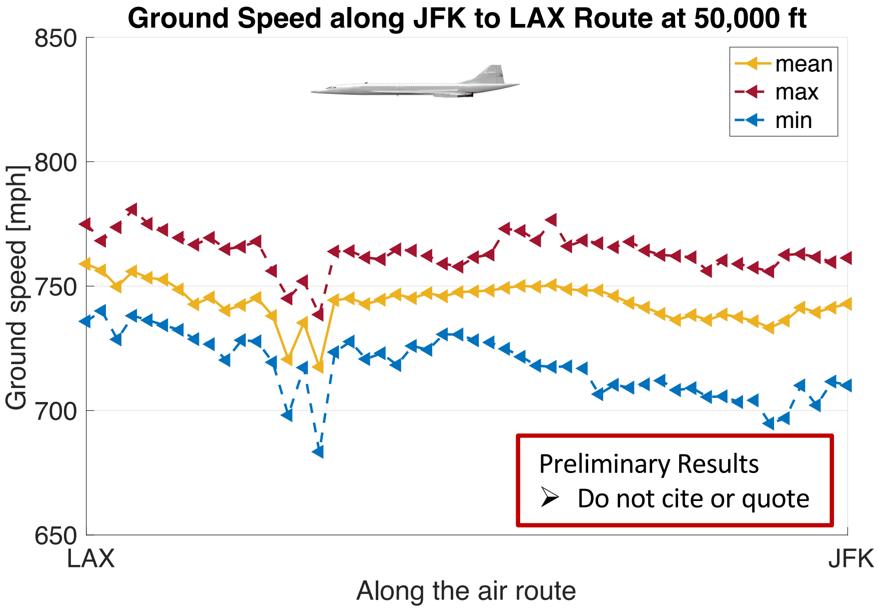
Ground speed for LAX-JFK route in 2017


Ground Speed along LAX to JFK Route at 50,000 ft

Preliminary Results
- ➢ Do not cite or quote


Ground Speed along JFK to LAX Route at 50,000 ft

Preliminary Results
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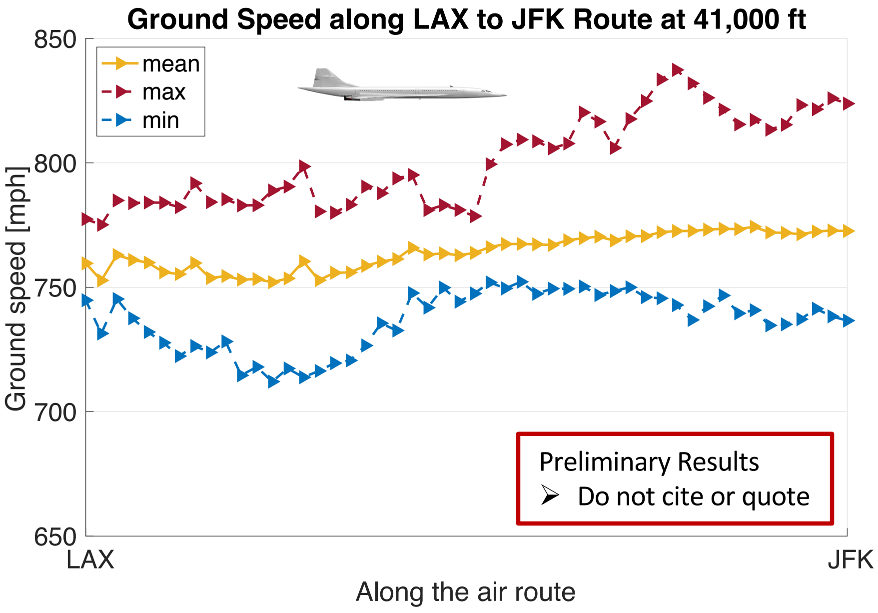
Ground Speed along LAX to JFK Route at 41,000 ft

Preliminary Results
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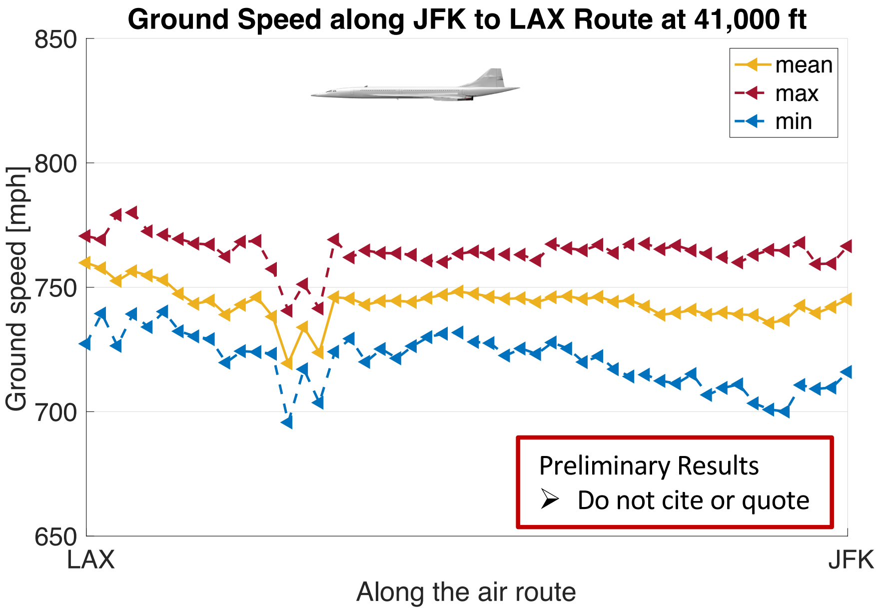
Ground Speed along JFK to LAX Route at 41,000 ft

Preliminary Results
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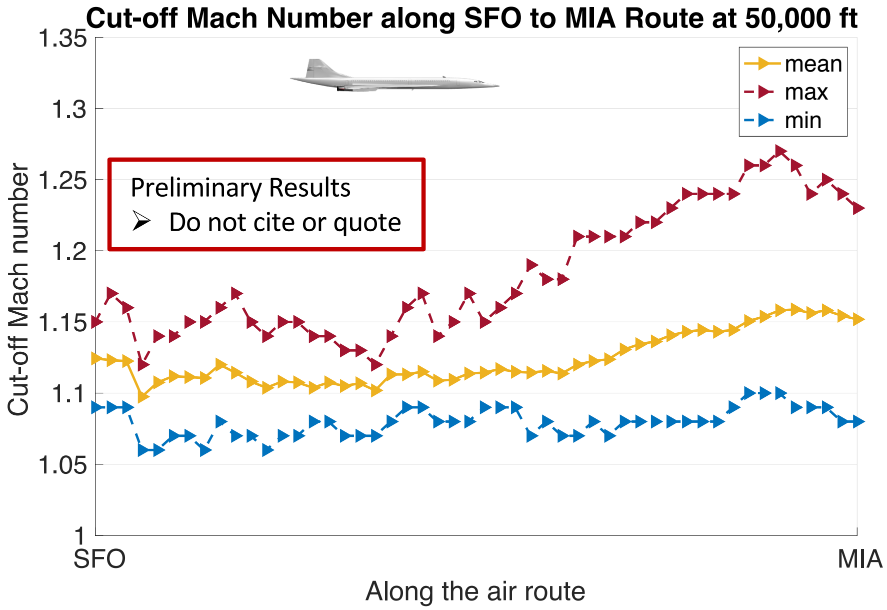
Cut-off Mach number for SFO-MIA route in 2017


Cut-off Mach Number along SFO to MIA Route at 50,000 ft

Preliminary Results
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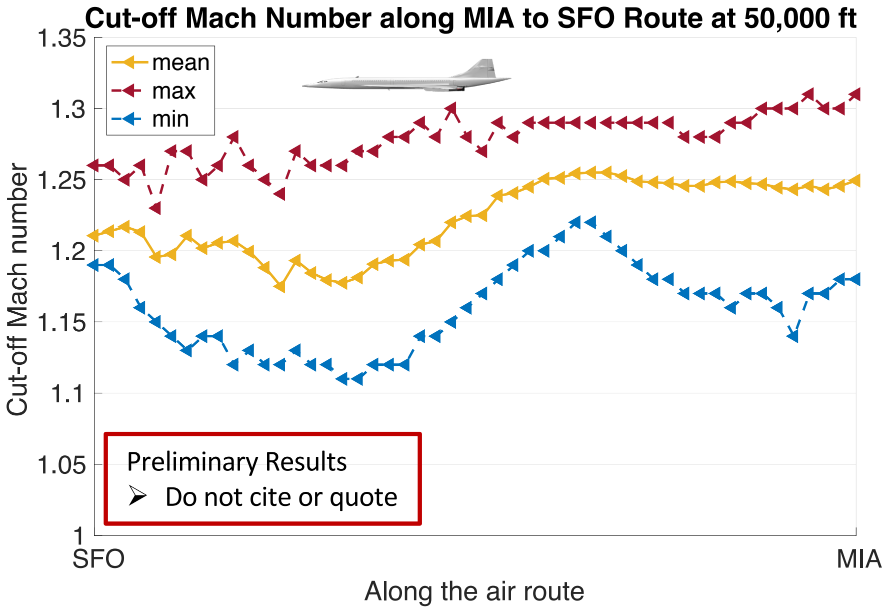
Cut-off Mach Number along MIA to SFO Route at 50,000 ft

Preliminary Results
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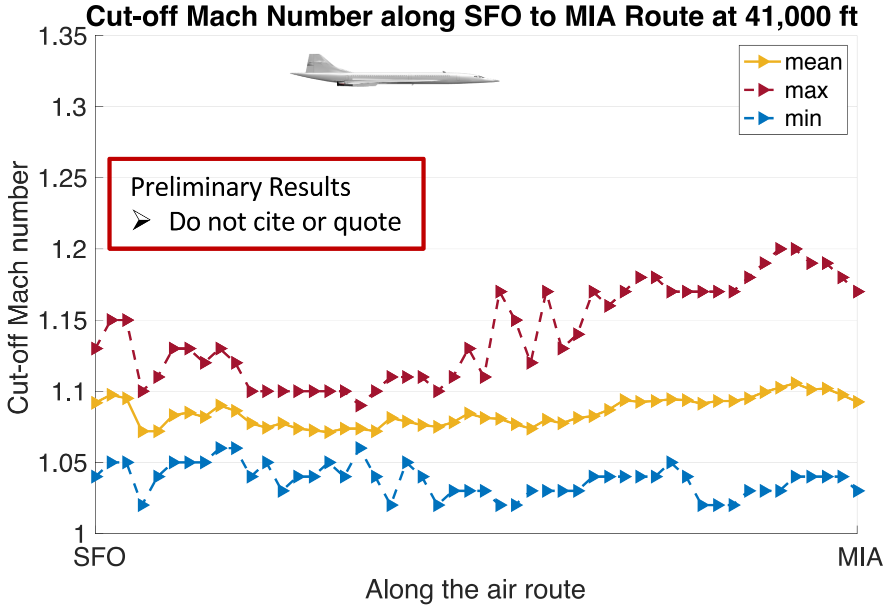
Cut-off Mach Number along SFO to MIA Route at 41,000 ft

Preliminary Results
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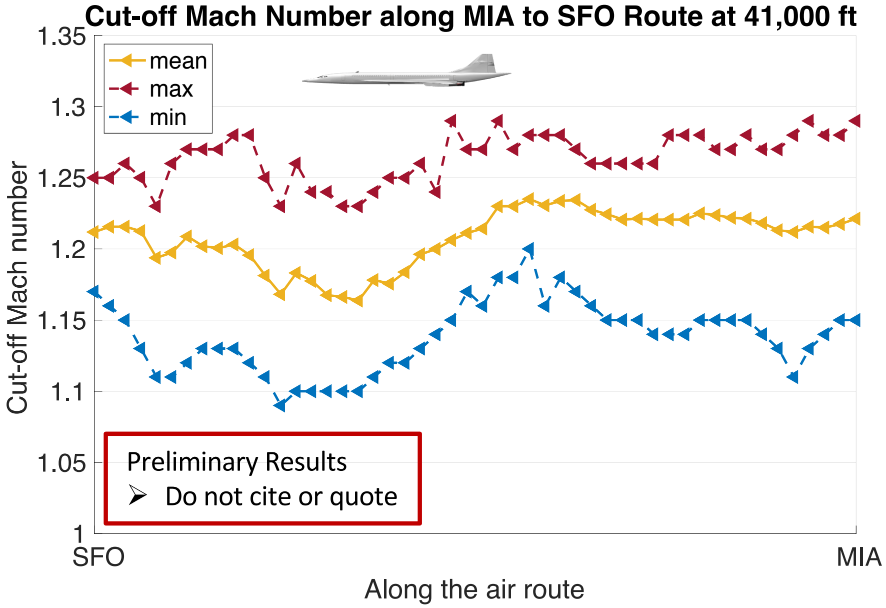
Cut-off Mach Number along MIA to SFO Route at 41,000 ft

Preliminary Results
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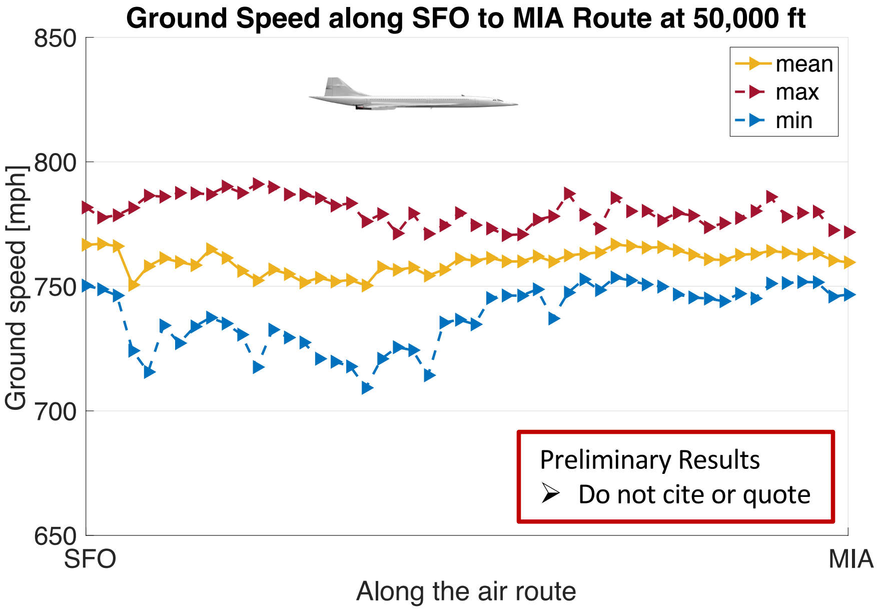
Ground speed for SFO-MIA route in 2017


Ground Speed along SFO to MIA Route at 50,000 ft

Preliminary Results
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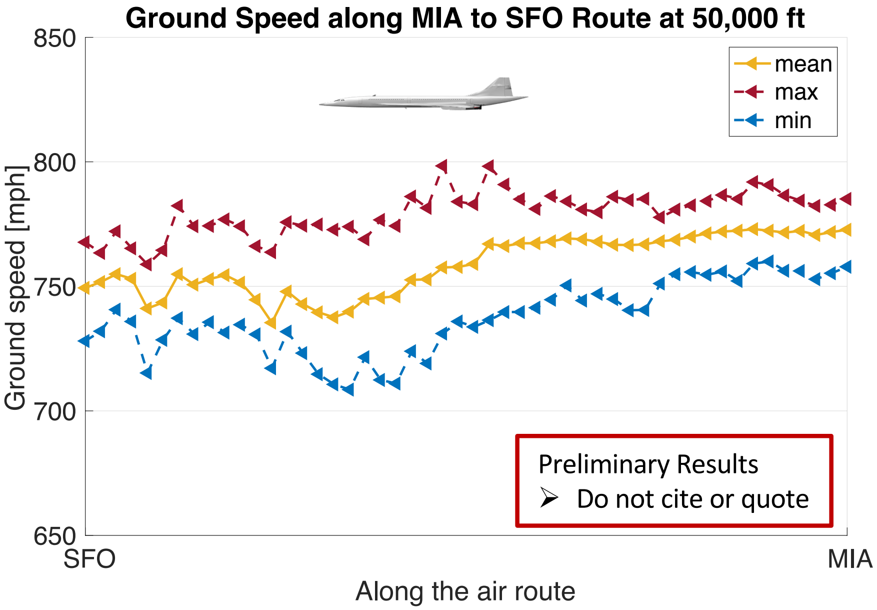
Ground Speed along MIA to SFO Route at 50,000 ft

Preliminary Results
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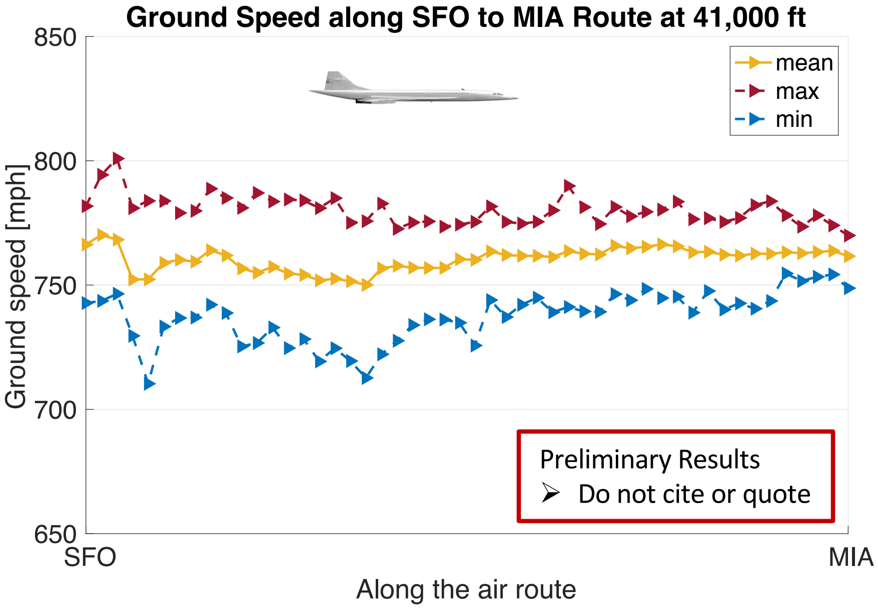
Ground Speed along SFO to MIA Route at 41,000 ft

Preliminary Results
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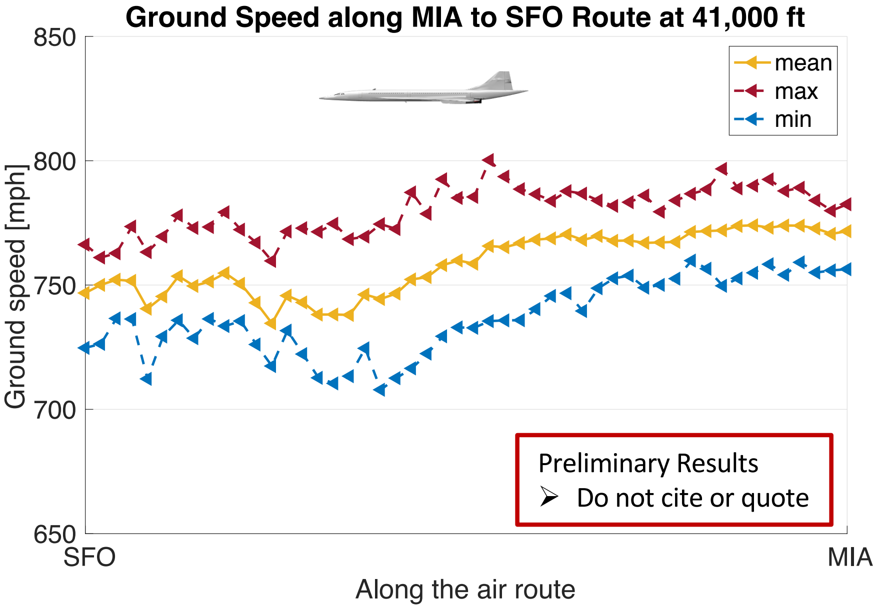
Ground Speed along MIA to SFO Route at 41,000 ft

Preliminary Results
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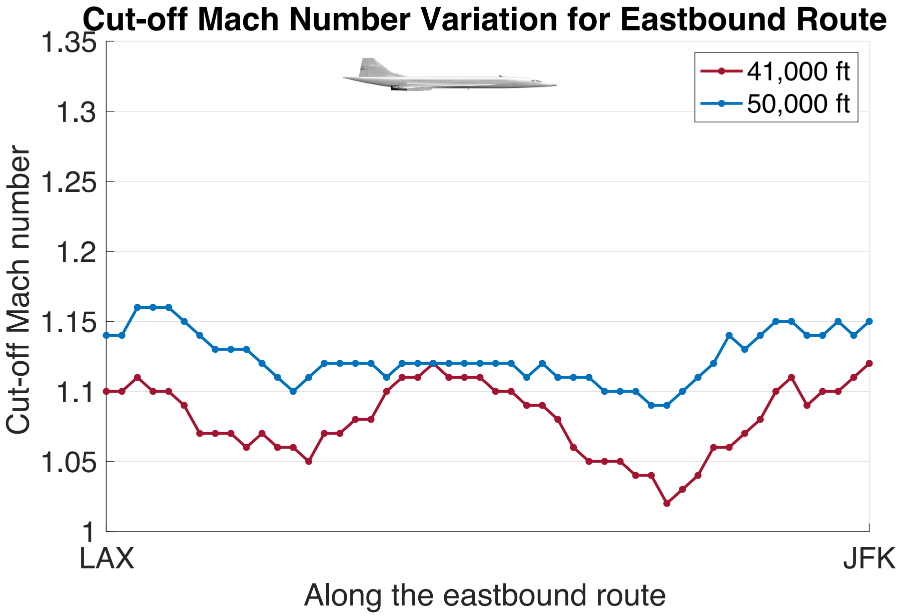
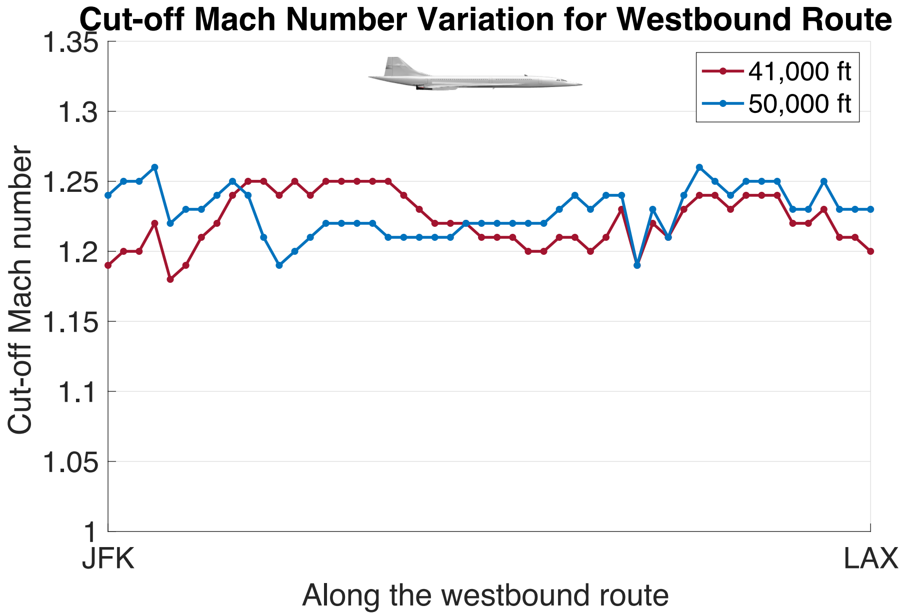
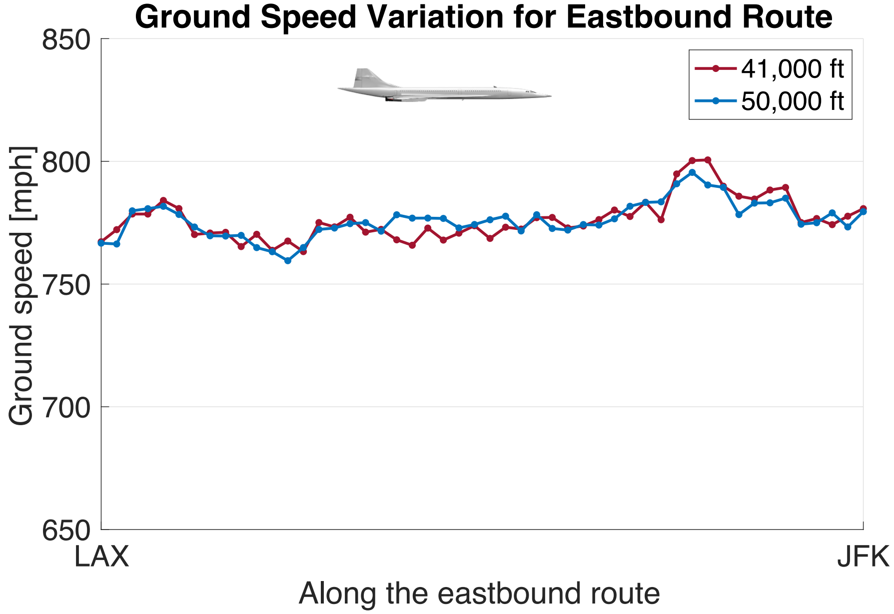
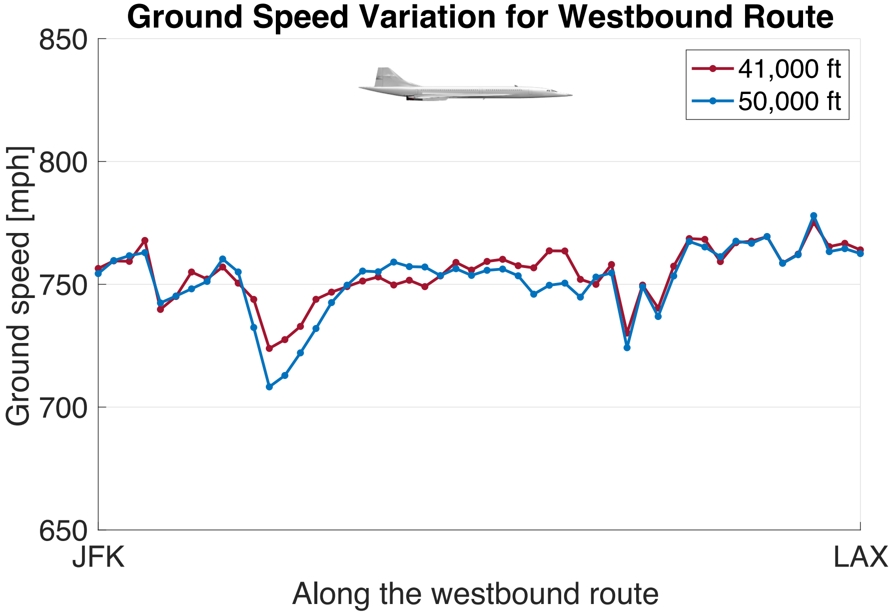
Impact of flight altitude on Mach cut-off

- LAX–JFK route, 6 PM UTC (2 PM EDT), Jul 1, 2017


Cut-off Mach Number Variation for Eastbound Route


Cut-off Mach Number Variation for Westbound Route


Ground Speed Variation for Eastbound Route


Ground Speed Variation for Westbound Route

Ray-tracing Conclusions

- **Very often** Mach cut-off operations will work.
- It's easier to enable Mach cut-off for a westbound flight than a eastbound flight.
- Must account for both atmospheric condition and ground elevation.
- Flight altitudes affect the flight cut-off Mach numbers, but only minimally impact the max aircraft ground speed.
- Haglund and Kane's formula works well, if CAREFULLY applied.

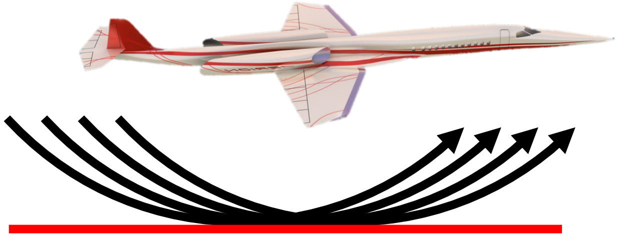
Switch gears: Perceptual study

- Overall perceptual study objective: To provide guidance in creation of metric-based regulations of Mach cut-off flight based on human perception

- Individual study objectives:
  1. Mach Cut-off **Descriptor** study
     - Identify terms appropriate for describing ground recordings of Mach-cutoff flight
  2. **Factors** of ***Annoyance*** study
     - Identify perceptual attributes contributing to annoyance and appropriate metrics to predict these characteristics
  3. **Degree** of **Annoyance** and **Relative Preference**
     - Compare Mach cut-off to road, rail, and subsonic aircraft noise.

Motivation: Perceived annoyance of Mach cut-off vs. other types of traffic noise

- If Mach cut-off flight was allowed over land, would the public find the noise acceptable?
- Study was designed to compare Mach cut-off flyover to
  - *Road*, *rail*, and *subsonic aircraft* traffic noise
  - Specifically: degree of annoyance and relative preference



versus

Approach: Traffic Noise Stimuli

- Recordings were used as stimuli for all 4 traffic types

Road

Rail

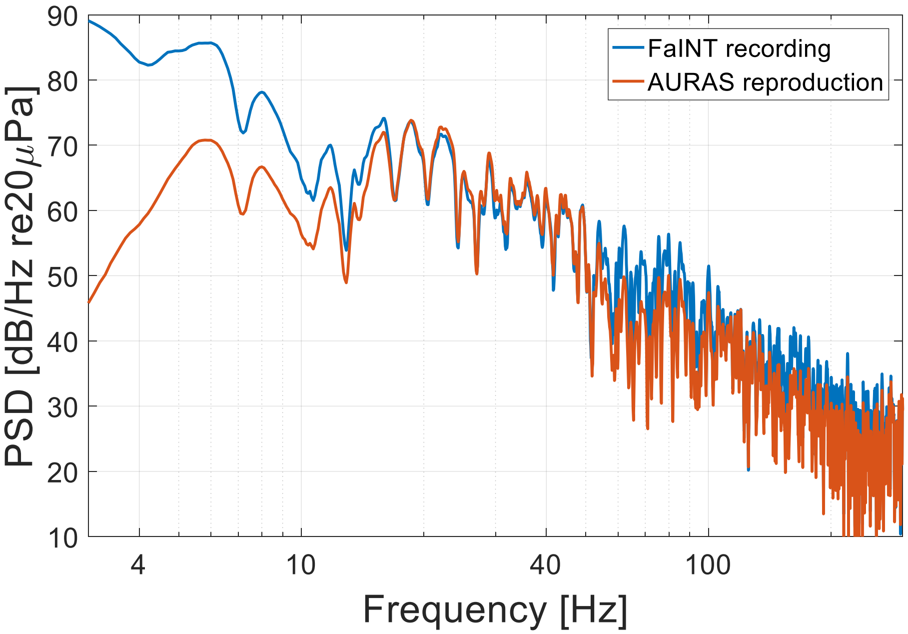
Subsonic Aircraft

Mach Cut-off
(NASA FAiNT study)

- 3 conditions were considered:
  1. **Outdoor stimuli**: levels adjusted to typical shortest distance
  2. **Indoor stimuli**: levels attenuated for a type of home construction
  3. **Level-equalized stimuli**: levels adjusted to be approximately the same using SEL-B and SEL-E weightings

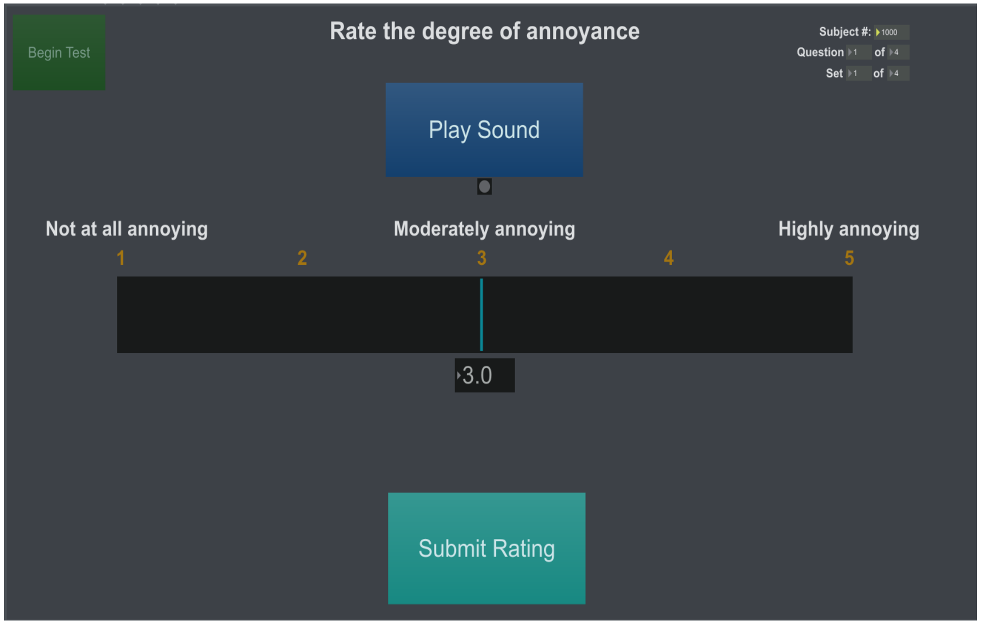
Traffic noise stimuli were played back over a 32 loudspeaker array

- Reproduction facility is in an anechoic chamber and includes 30 2-way speakers and 2 subwoofers



Differences in perception evaluated in 2 ways: Annoyance and Preference Order

1. Annoyance Ratings

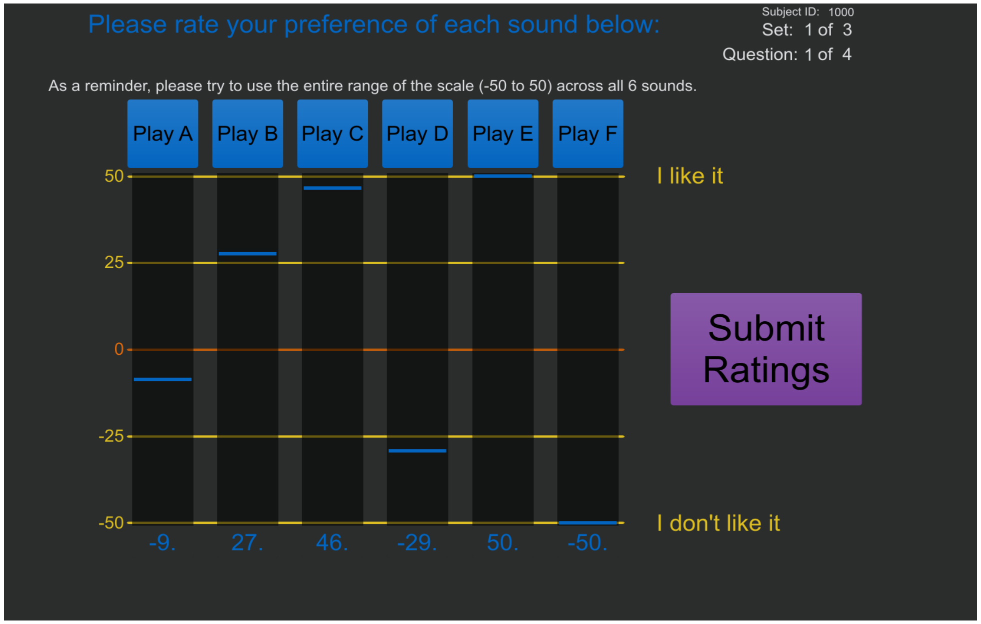


Rate the degree of annoyance

Subject #: 1000
Question 1 of 4
Set 1 of 4

- Each sound sample is rated individually based on degree of annoyance

2. Preference Rankings



Please rate your preference of each sound below:

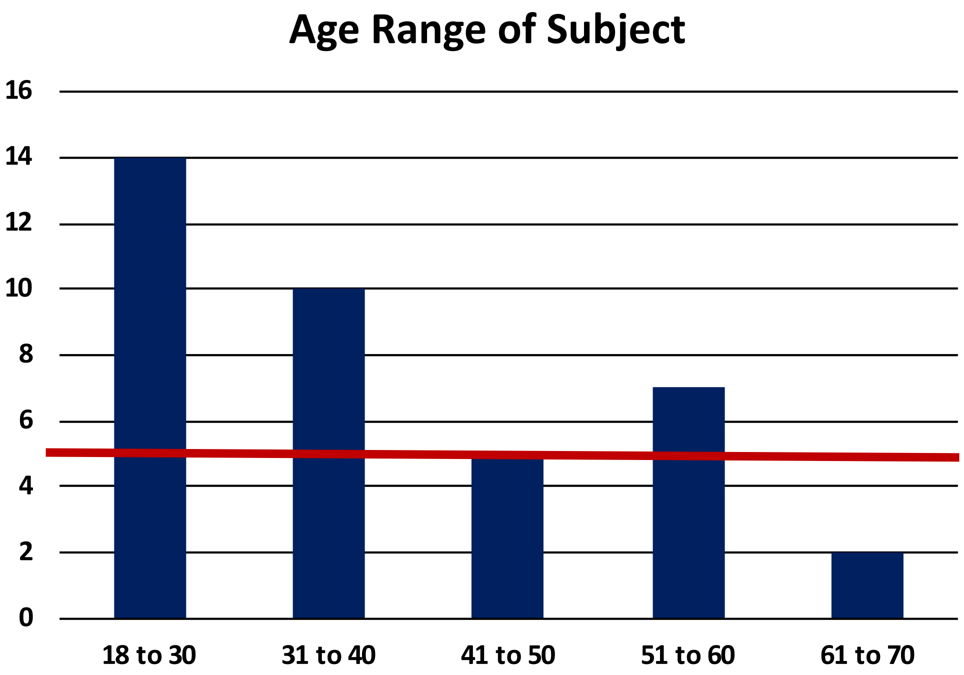
Subject ID: 1000
Set: 1 of 3
Question: 1 of 4

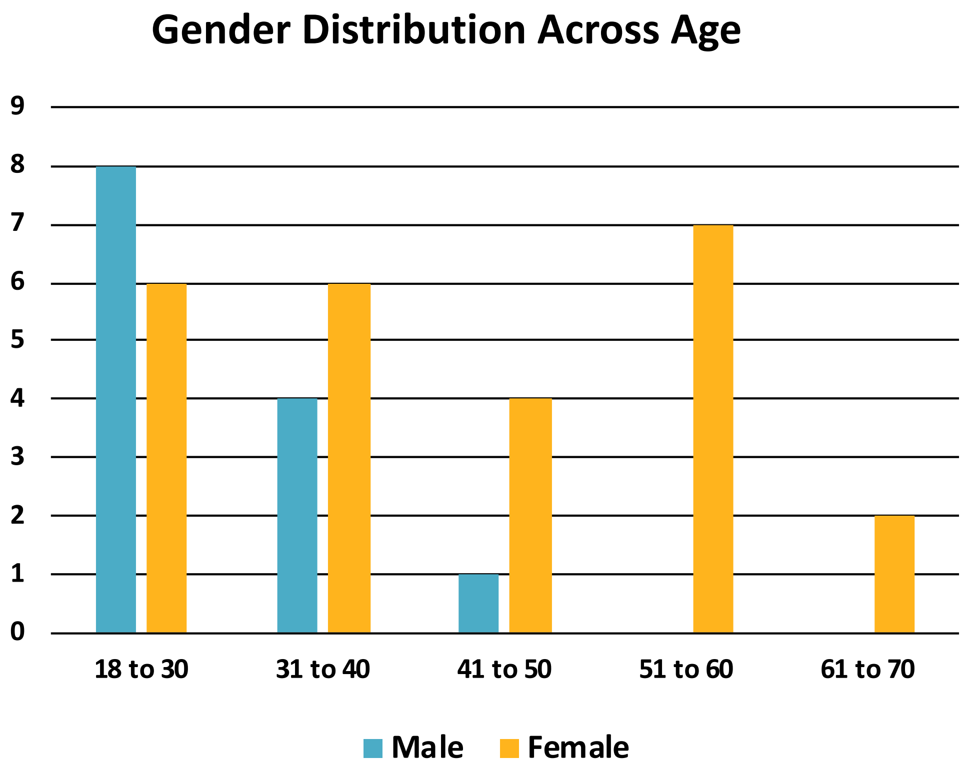
As a reminder, please try to use the entire range of the scale (-50 to 50) across all 6 sounds.

- Multiple sound samples are ranked simultaneously according to preference

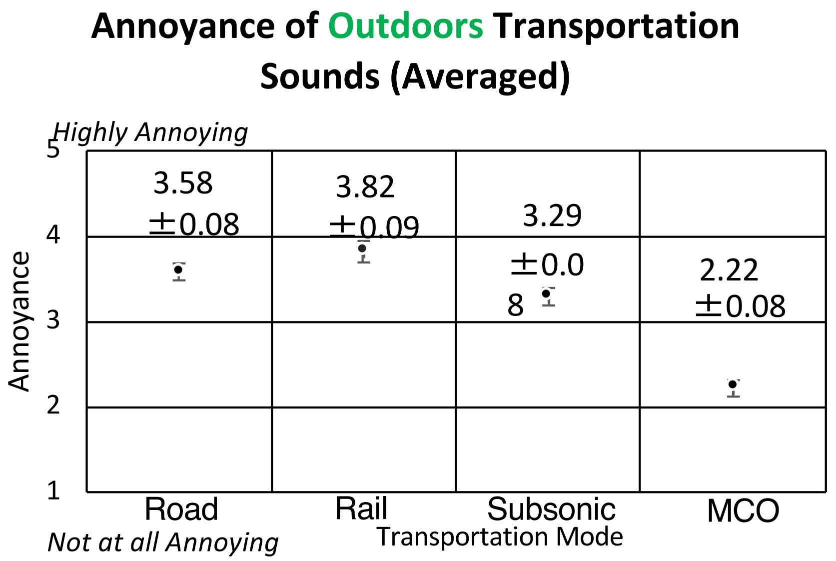
Results: 38 subjects participated in the study 18-70 yrs. old (37.3±13.5)

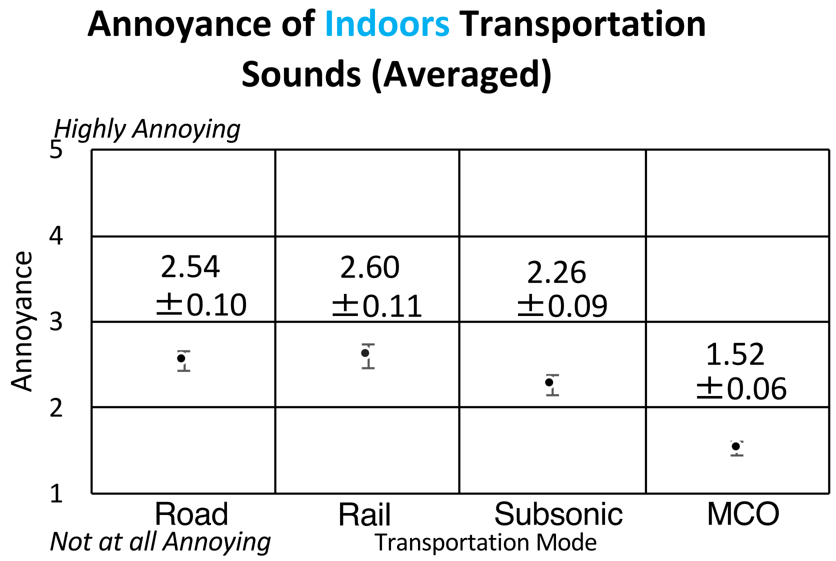
- Criteria: Hearing thresholds 35 dB or lower (250 – 8k Hz)





Mach-Cutoff is the least annoying transportation mode for all 3 conditions evaluated





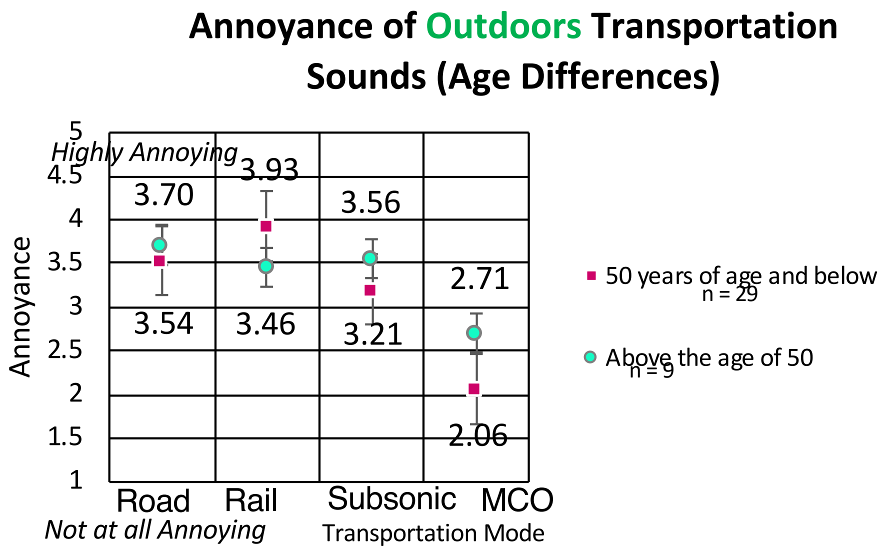
Road Stimuli: Various traffic densities (3) and Jake brake (1)

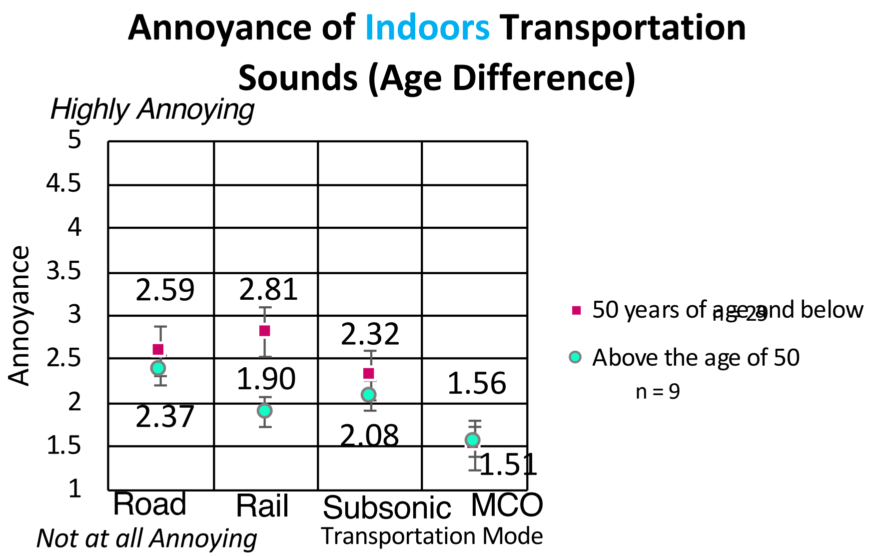
Rail Stimuli: Screeching brakes (1), train horn (1), train pass (2)

Subsonic Stimuli: Various aircraft sizes and landing or take-off

MCO Stimuli: Selection of stimuli from NASA FAiNT recordings

Subjects over the age of 50 find MCO signatures more annoying when envisioning they are outdoors


Annoyance of Outdoors Transportation Sounds (Age Differences)


Annoyance of Indoors Transportation Sounds (Age Difference)

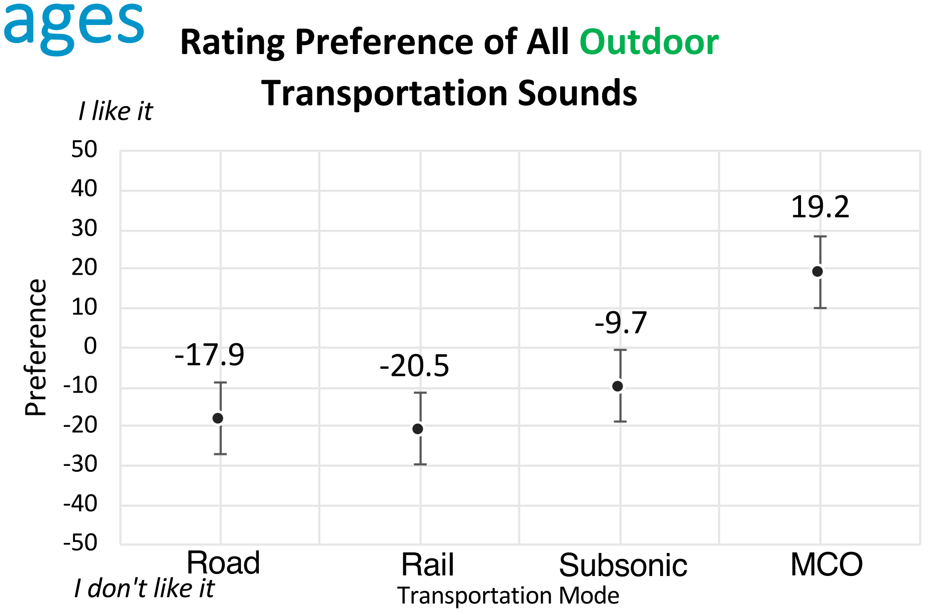
Road Stimuli: Various traffic densities (3) and Jake brake (1)

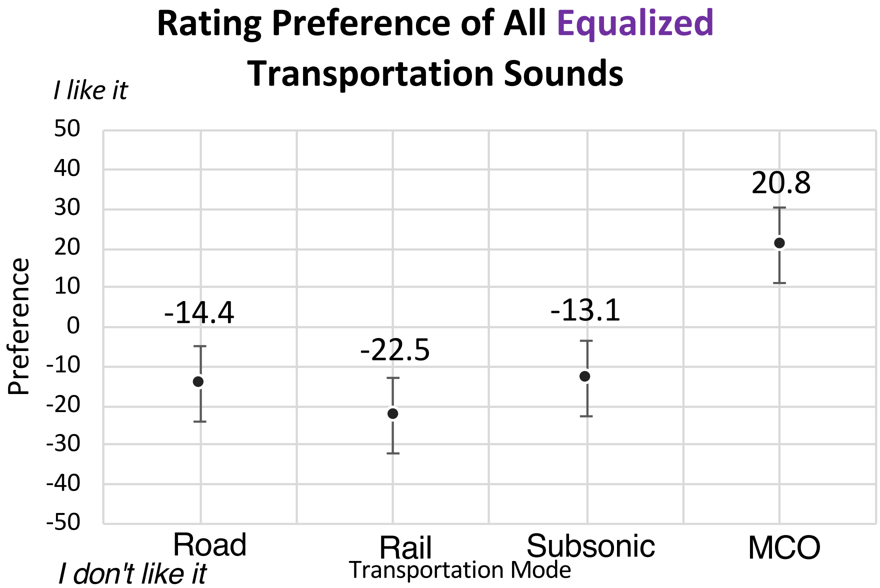
Rail Stimuli: Screeching brakes (1), train horn (1), train pass (2)

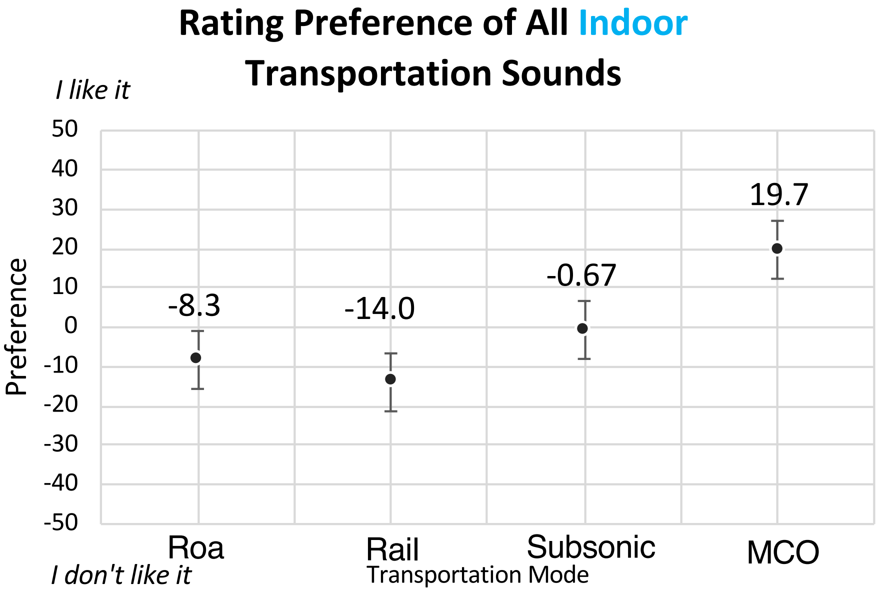
Subsonic Stimuli: Various aircraft sizes and landing or take-off

MCO Stimuli: Selection of stimuli from NASA FAiNT recordings

Mach-Cutoff is the most preferable transportation mode when averaged across all ages


Rating Preference of All Outdoor Transportation Sounds


Rating Preference of All Equalized Transportation Sounds

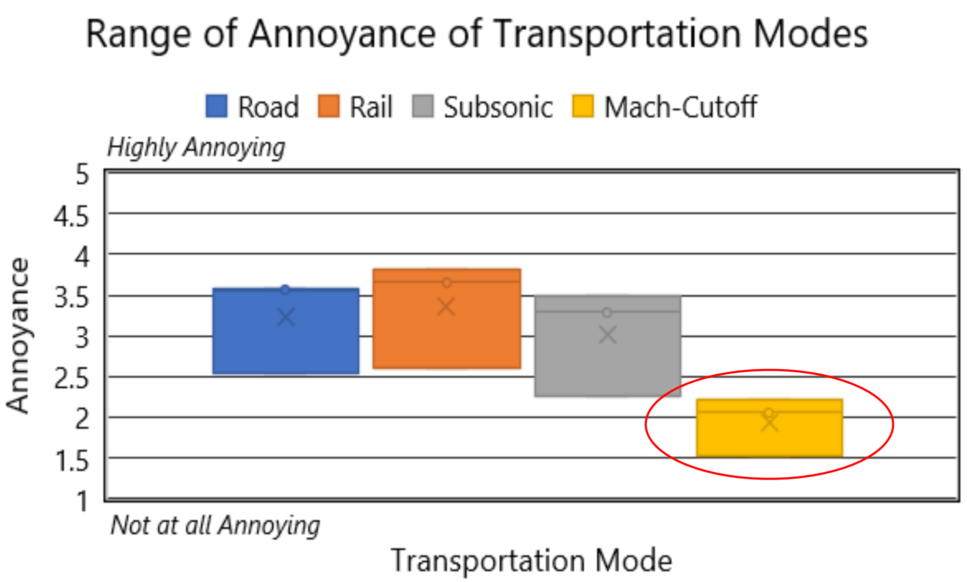

Rating Preference of All Indoor Transportation Sounds

Key results:

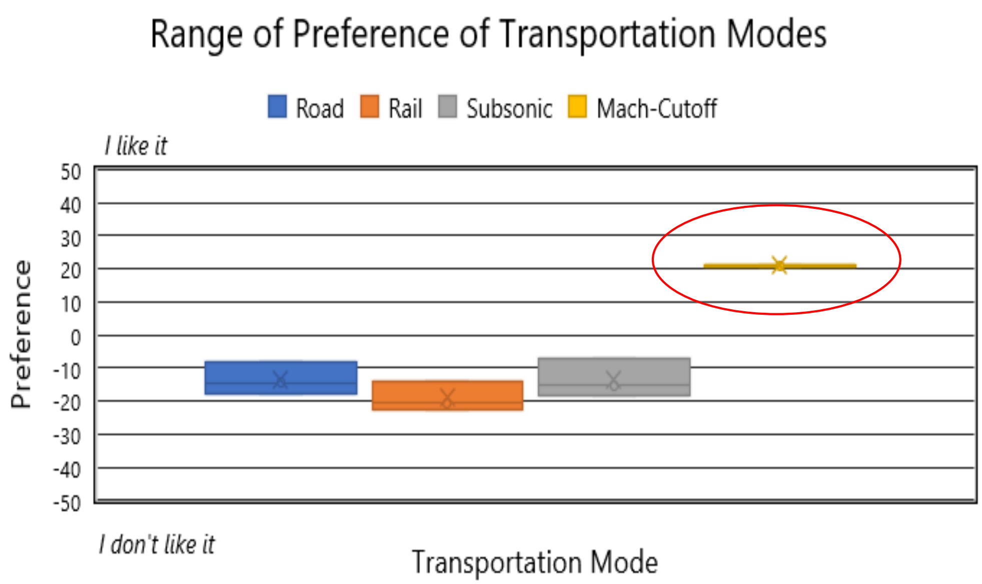
- Mach-Cutoff is preferable compared for all 3 conditions
- Rail is the least preferable transportation mode
  - Rail stimuli include horns and brakes screeching

Perceptual Study Conclusions

Annoyance



Preference



Based on this study, there is no evidence to indicate that Mach-Cutoff signatures are more annoying and less preferable to road, rail, and subsonic aircraft noise.

Overall Conclusions for Project 42

- Project 42 is now concluding.
- Knowing the atmosphere is critical for enabling Mach cut-off operations. If you know the atmosphere, you will be able to fly Mach cut-off with a good margin of safety and avoid focus booms on the ground.
- If the public does hear the distinctive Mach cut-off sounds, we believe they will be of lesser impact compared to road, rail, or subsonic aircraft noises.
- In the future, field testing should be conducted to confirm the results from Project 42.

Thanks for the opportunity to do this work!

Acknowledgements

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Participants

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- The Pennsylvania State University
  Victor W. Sparrow, Project Director, and Penn State ASCENT PI
  Michelle C. Vigeant, Project Co-Investigator
  Zhendong Huang, Nicholas Ortega, Jonathan Broyles
- Volpe National Transportation Systems Center
  Juliet Page

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Backup slides

The outdoor transportation sound samples are attenuated to represent real listening scenarios

- Transportation sound samples are attenuated based on researched distances to generate the outdoor stimuli

Road

Houston, I-45

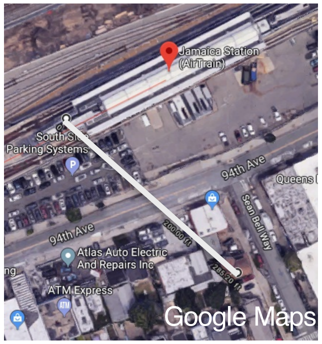
Distance:
185 ft, 57 m

Atlanta, I-85

Distance:
260 ft, 80 m

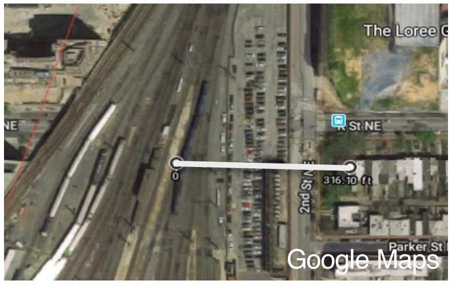
Rail

NYC, Jamaica Station



Distance: 285 ft, 87 m

Washington, D.C. Union Station



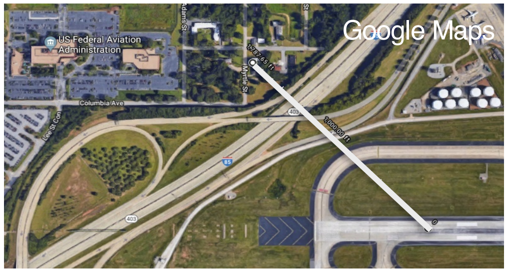
Distance: 315 ft, 96 m

Subsonic

Chicago, ORD Airport

Distance:
3230 ft, 985 m

Atlanta, ATL Airport



Distance:
1790 ft, 546 m

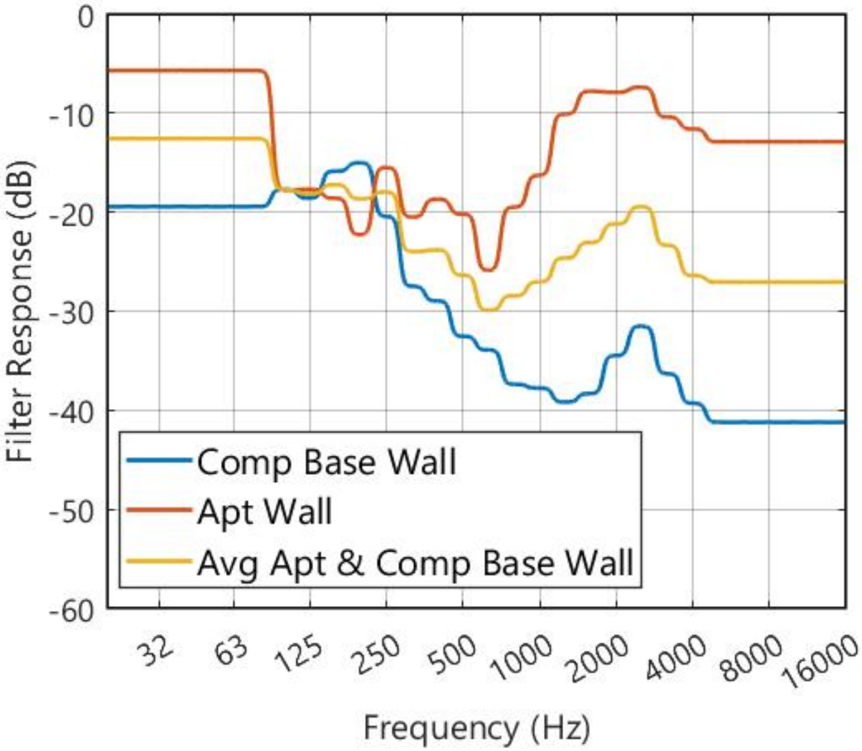
The indoor transportation sound samples are filtered to represent real listening scenarios

- A typical exterior composite wall construction is used to generate the indoor sound samples
  - 2x6 Wood Stud Exterior Wall
  - Composite Wall Construction
    - 35% of wall area are windows
    - 4% of wall area is a door


Google Maps

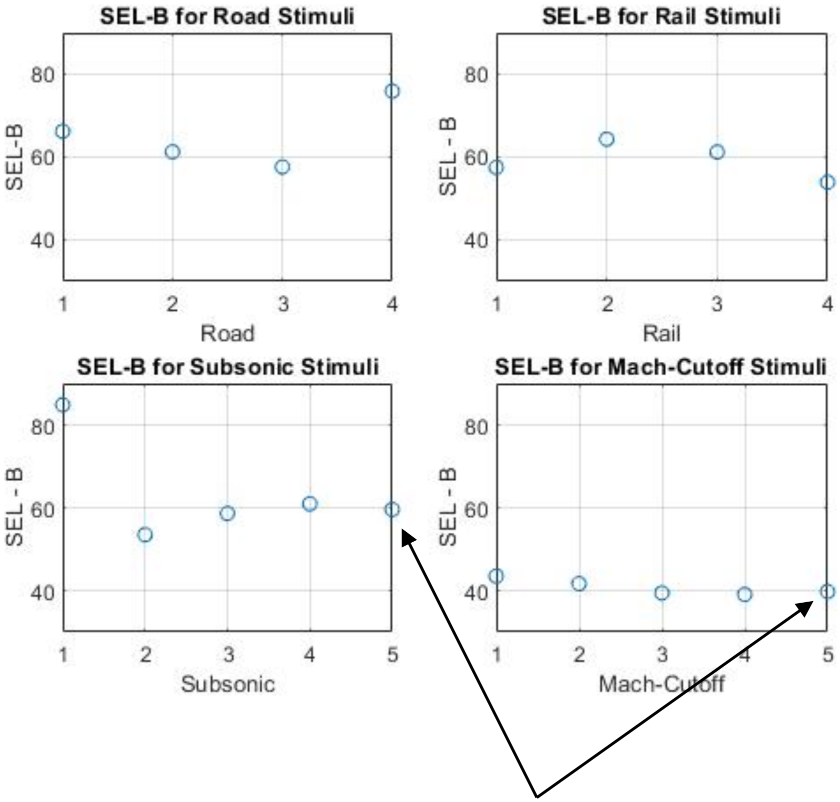

Google Maps

- Compared to transmission loss data of apartment along I-99

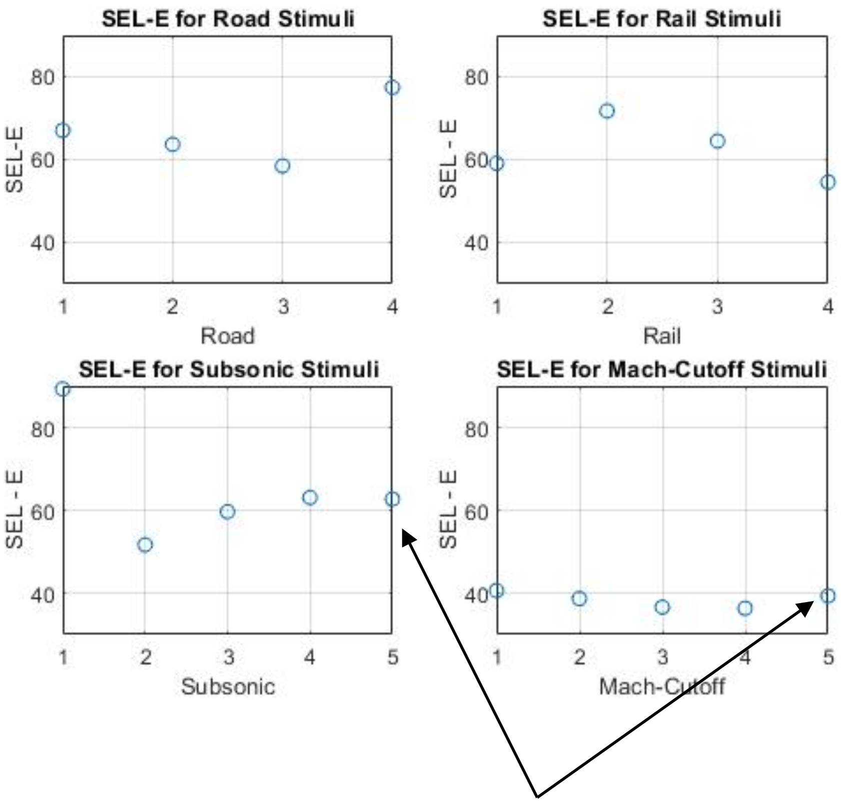


SEL-B and SEL-E was selected for stimuli equalization

Sound Exposure Level B and E Weighting for All Stimuli

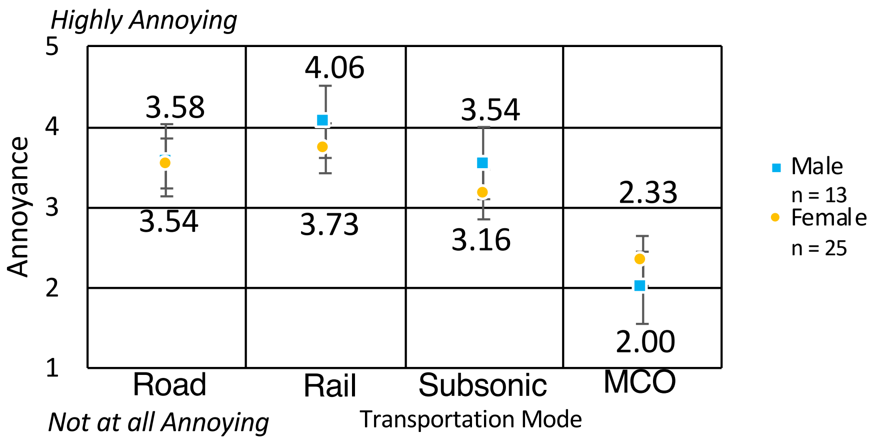


References used in Preference Part of Study

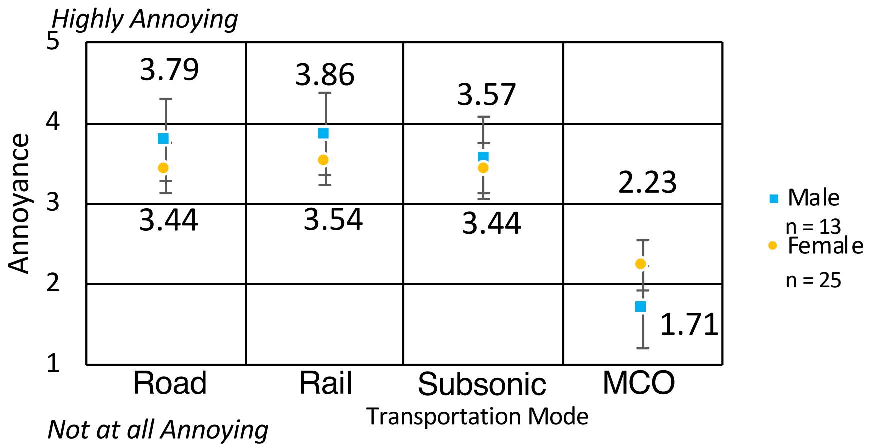


References used in Preference Part of Study

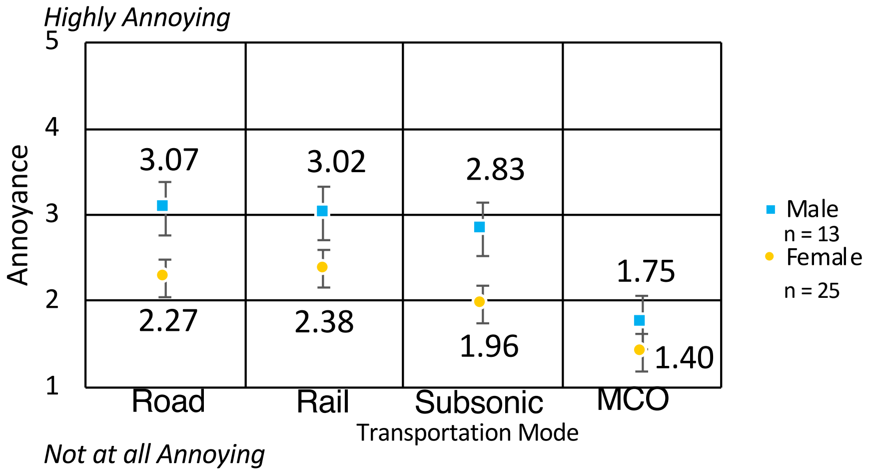
Male subjects were more annoyed when envisioning they are indoors



Annoyance of Outdoors Transportation Sounds (Gender - All)



Annoyance of Equalized Transportation Sounds (Gender - All)



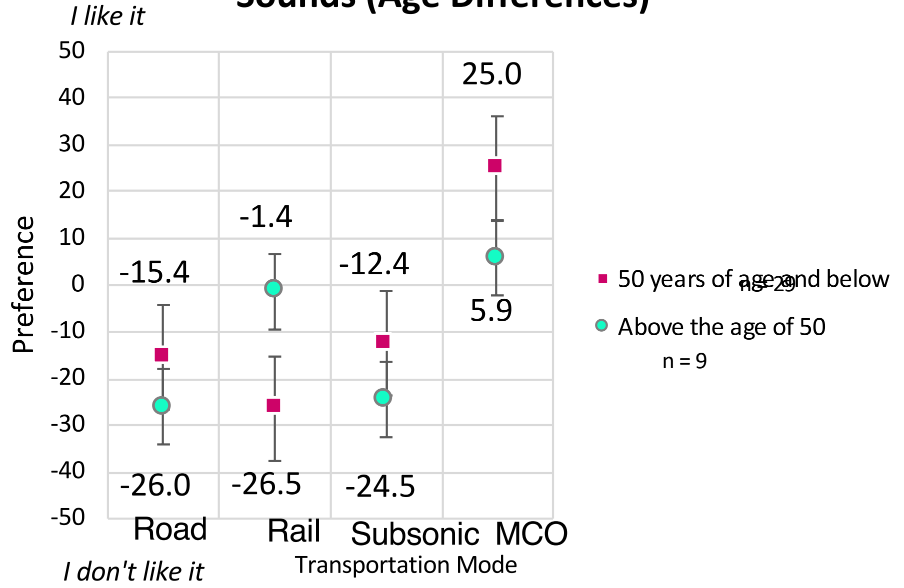
Annoyance of Indoors Transportation Sounds (Gender - All)

Road Stimuli: Various traffic densities (3) and Jake brake (1) **Rail** Stimuli: Screeching brakes (1), train horn (1), train pass (2) **Subsonic** Stimuli: All similar (LTO) (4) **MCO** Stimuli: All similar (NASA FaINT) (4)

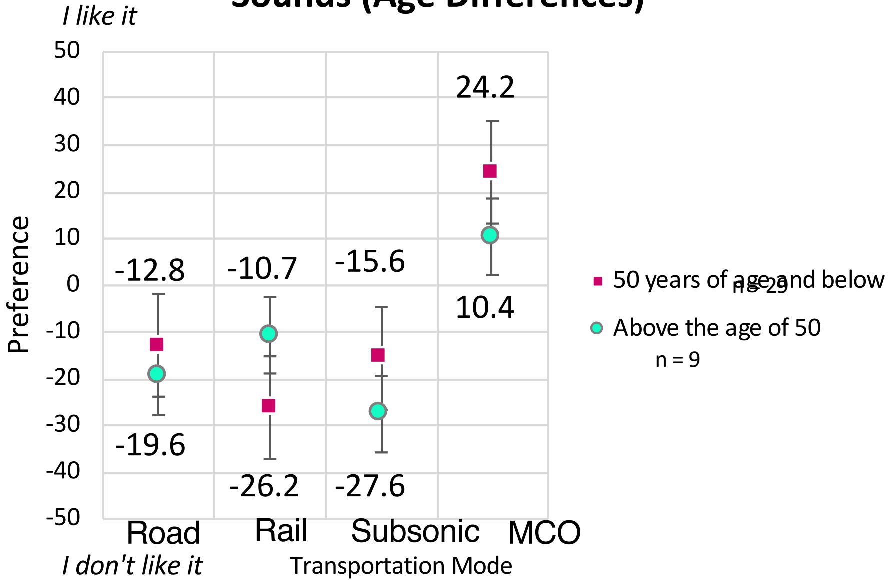
Key results:

- No differences between genders when envisioning that they are outdoors
- Males find Road, Rail, and Subsonic sounds more annoying when envisioning that they are indoors
  - May be due to the number of male participants

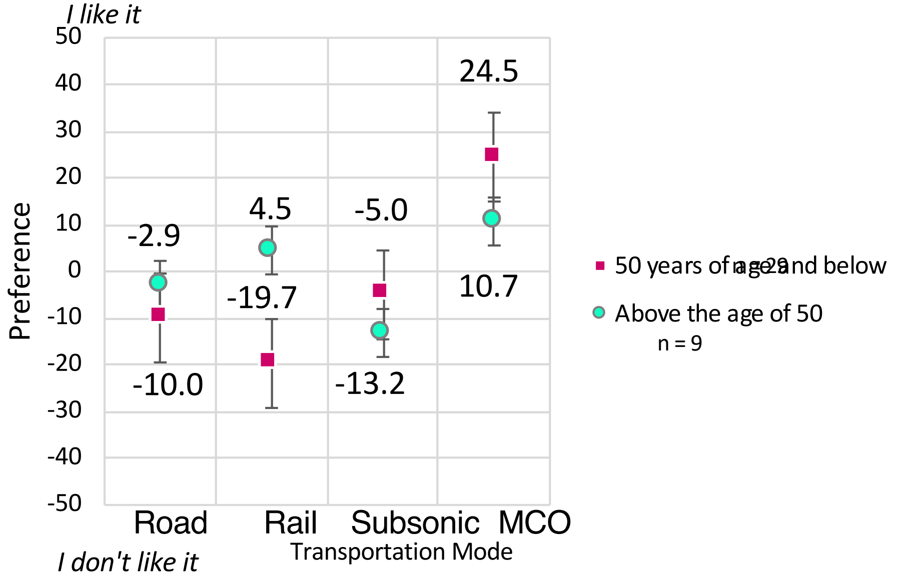
Preference shows same trends as Annoyance for subjects above the age of 50



Preference of Outdoor Transportation Sounds (Age Differences)



Preference of Equalized Transportation Sounds (Age Differences)



Preference of Indoor Transportation Sounds (Age Differences)

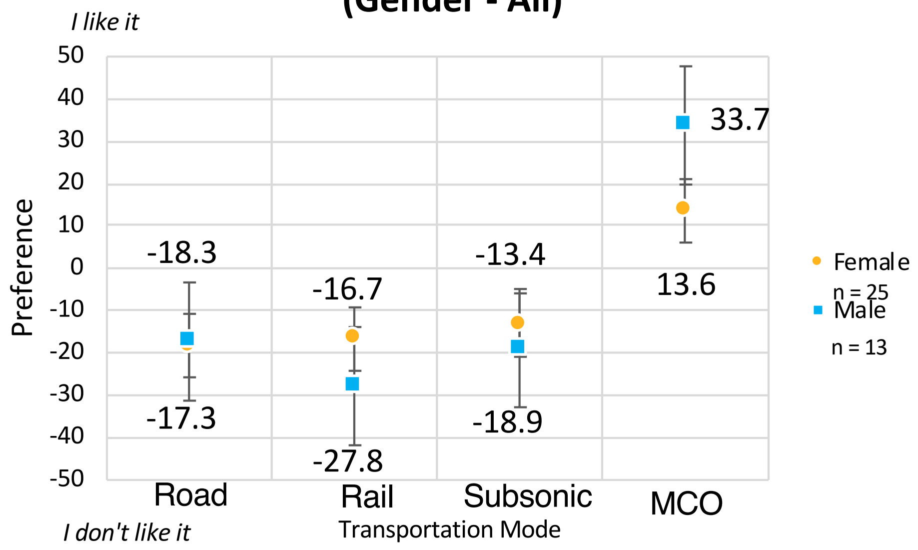
Road Stimuli: Various traffic densities (3) and Jake brake (1)
Rail Stimuli: Screeching brakes (1), train horn (1), train pass (2)
Subsonic Stimuli: All similar (LTO) (4)
MCO Stimuli: All similar (NASA FaINT) (4)

Key results:

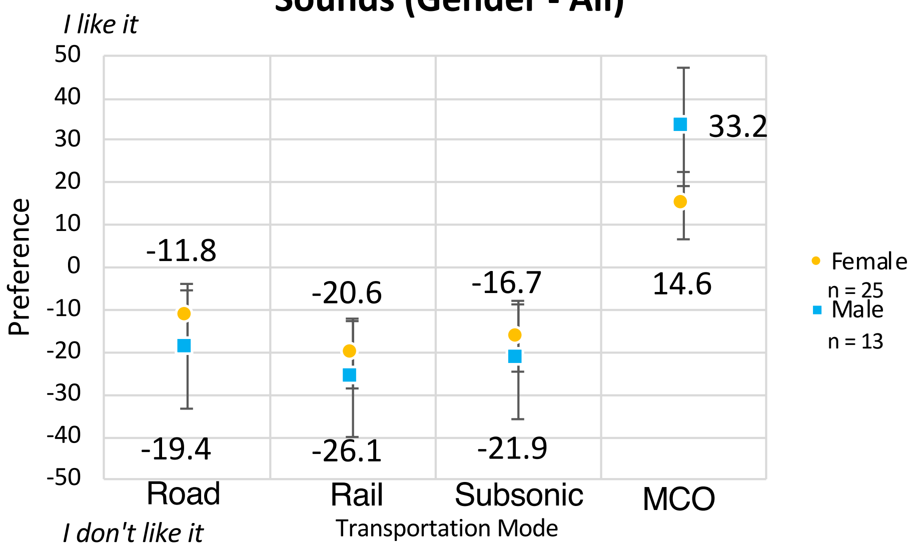
- Mach-Cutoff is not as preferable to subjects above the age of 50
  - Only for Outdoor and Indoor sets
  - Mach-Cutoff is still the most preferable transportation mode
- Subjects above the age of 50 prefer Rail sounds more than younger subjects
- No statistical differences for Road and subsonic sounds

Gender has little effect on the preference of transportation modes

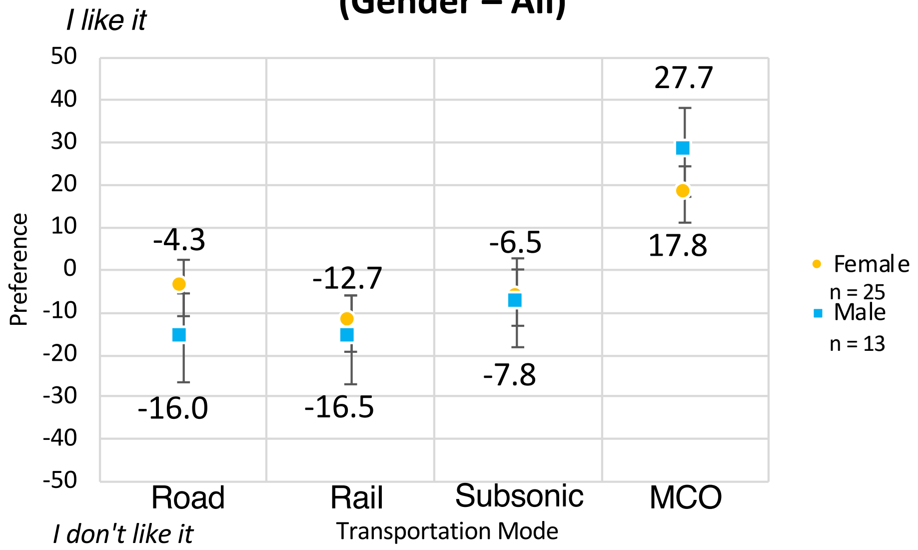
Preference of Outdoor Transportation Sounds (Gender - All)



Preference of Equalized Transportation Sounds (Gender - All)



Preference of Indoor Transportation Sounds (Gender – All)



Road Stimuli: Various traffic densities (3) and Jake brake (1) **Rail** Stimuli: Screeching brakes (1), train horn (1), train pass (2) **Subsonic** Stimuli: All similar (LTO) (4) **MCO** Stimuli: All similar (NASA FaINT) (4)

Key results:

- Preference ratings are very similar between the genders for Road, Rail, and Subsonic for all sets
- While Mach-Cutoff appears to be more preferable for male subjects than female subjects, but not statistical different