Boeing 737-800 and MAX 8 Critical Factor Simulation

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Abstract

Boeing 737 is one of the most widely used aircraft in hundreds of airlines around the world. The Boeing Company introduced the new modified series of the 737 family Boeing 737 MAX series in 2015 and the Boeing 737 MAX 8 entered the commercial service in 2016. The MAX 8 is a state of the art aircraft that is more computerized and modified using the application of improved aerodynamics and safety systems. But since the crashes of Lion Air JT610 and Ethiopian Airlines ET302 which were operated with Boeing 737 MAX 8 aircraft, the global MAX 8 fleet became grounded officially due to safety reasons. The investigations said the activation of the MCAS (A safety system) played major roles in both crashes. In this research, the other factors except for the MCAS which are, take-off angles, stall angle and stall times, and V1 &V2 speeds of the MAX8 were simulated and compared with its predecessor Boeing 737-800 using the Microsoft Flight Simulator X.

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Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Boeing is one of the leading aircraft and aerospace crafts manufacturers that designed most of the glorious jets in civil aviation for more than half a century. Boeing 737, Boring 747 and Boeing 777 are some of the most widely used passenger jets in the civil aviation industry today. The Boeing 737 family is still a giant in the industry used by more than 90% of the airlines across the world. The most popular and widely used Boeing 737-800 is the best design so far by the Boeing, because of the improved stability and the safety systems. Boeing 737 MAX 8 was introduced under the Boeing 737 MAX series in 2016 to improve and increases the value of the Boeing 737 aircraft by taking it to the next generation civil aviation operations more safely and efficiently. The aircraft was a success until two of the Boeing 737 MAX 8 aircraft faced two fatal crashes leaving no survivors. The Lion Air flight JT610 and Ethiopian Airlines flight ET302 operated by two MAX 8 aircraft crashed minutes after the take-offs. There both crashes and the clues showed similar characteristics and behaviours in their investigations. The new stall avoiding system added on board the MAX 8 called the

Manoeuvring Characteristics Augmentation System or the MCAS has given a major contribution for both crashes according to the investigation reports by the FAA and NTSB. And as a result the entire Boeing 737 MAX 8 fleet was officially grounded in 2019 since the aircraft is considered to be less reliable and unpredictable.

In this research, the Boeing 737 MAX 8 is compared and tested with the Boeing 737-800 to observe and determine the critical factors (except MCAS) of both aircraft. For the simulation purpose, Microsoft Flight Simulator X was used.

Nomenclature
MCAS - Manuevering Characteristics Augmentation System
V1 **-** The speed where the aircraft exceeds the point of stopping on the runaway in case of a take-off aboard.
V2 **-** The minimum speed that the aircraft will be able to climb in case of a one engine failure.
Vr **-** The speed or the point where the pilot stats to pitch the nose up to lift off from the runaway.
AOA **-** Angle of Attack

2. Materials and Methods

To conduct simulation and to test the behaviors of critical factors in Boeing 737-800 and MAX 8, Microsoft Flight Simulator X was used. For the Data analysis and the representative purpose Microsoft Office package, 2016 was used mainly MS word for documentation and the MS Excel for data analysis. The Main and critical factor of the aircraft were identified as,

1. Take off angles (Pitch Angles)
2. V1 and V2 Speeds Comparison
3. Stall angle and Stall time comparison
4. Weight conditions comparisons
5. Evaluating the stability and other factors of Boeing 737-800 and MAX 8.

For determining the takeoff angles and V1, V2 speeds the simulations were conducted on the Microsoft flight simulator X. Stall angles and stall times were also determined using the simulations. Other critical factors were evaluated based on the secondary data and all the simulation setups and their initial conditions were given according to the international civil aviation standards regarding each aircraft model.

3. Simulations and Results

There are 8 flap settings on the 737-800, with each having a different angle. These different angles allow the pilots to control how much lift the wings generate. Here are the angles below.

Flaps 1 - *8°*
Flaps 2 - *11°*
Flaps 5 - *14°*
Flaps 10 - *19°*
Flaps 15 - *22°*
Flaps 25 - *26°*
Flaps 30 - *35°*
Flaps 40 - *46°*

8, various weight conditions.

Flaps and Airspeeds
You use different amounts of flaps in different airspeeds. If you want more lift, you need more flaps and vice versa. Here are the airspeeds in which each set of flaps should be used to prevent damage, and maximize lift.
Flaps Up - *210KTS*
Flaps 1 - *190KTS*
Flaps 5 - *170KTS*
Flaps 10 - *160KTS*
Flaps 30 - *130KTS*
Flaps 40 - *120KTS*
Flaps 2, 15, and 25 are not normally used during flight hence why they are not on this list. Flaps 5, 15, and 25 are primarily used for takeoffs. In adverse weather conditions, taxi with the wing flaps up and then set takeoff flaps during your Before Takeoff checklist procedure. When extending or retracting the flaps, use the next appropriate flap setting depending on whether you're slowing down or speeding up.

Source - https://community.infiniteflight.com/t/using-the-737-800-900-flaps/191982

3.1. Testing the pitch angles and trim positions
For this test both Boeing 737-800 and Boeing 737, Max 8 will use their take-off flaps position at Flaps 15. Flap position 15 is used because it is the middle value between flap position 5 and 25, which are generally used in the takeoff.
The elevator trim is Elevator 1.8 Upward pitch. Since both aircraft have balanced loads the elevator trim is only used to trim, not balancing.
The weather selected is the minimum wind speed and almost zero turbulences. Therefor any other trimming surfaces will not be used.

3.1.1. Boeing 737-800 takes off-angle data
Flaps 15 *Elevator* 1.8 upward *Fuel weight (At max)* - 20.762Ton *Airline*- Lion Air Boeing 737-800
Flight Number - Test 1 *Time* - 9.30 AM *Whether* - Clear skies
Location - San Francisco International Airport, California, USA

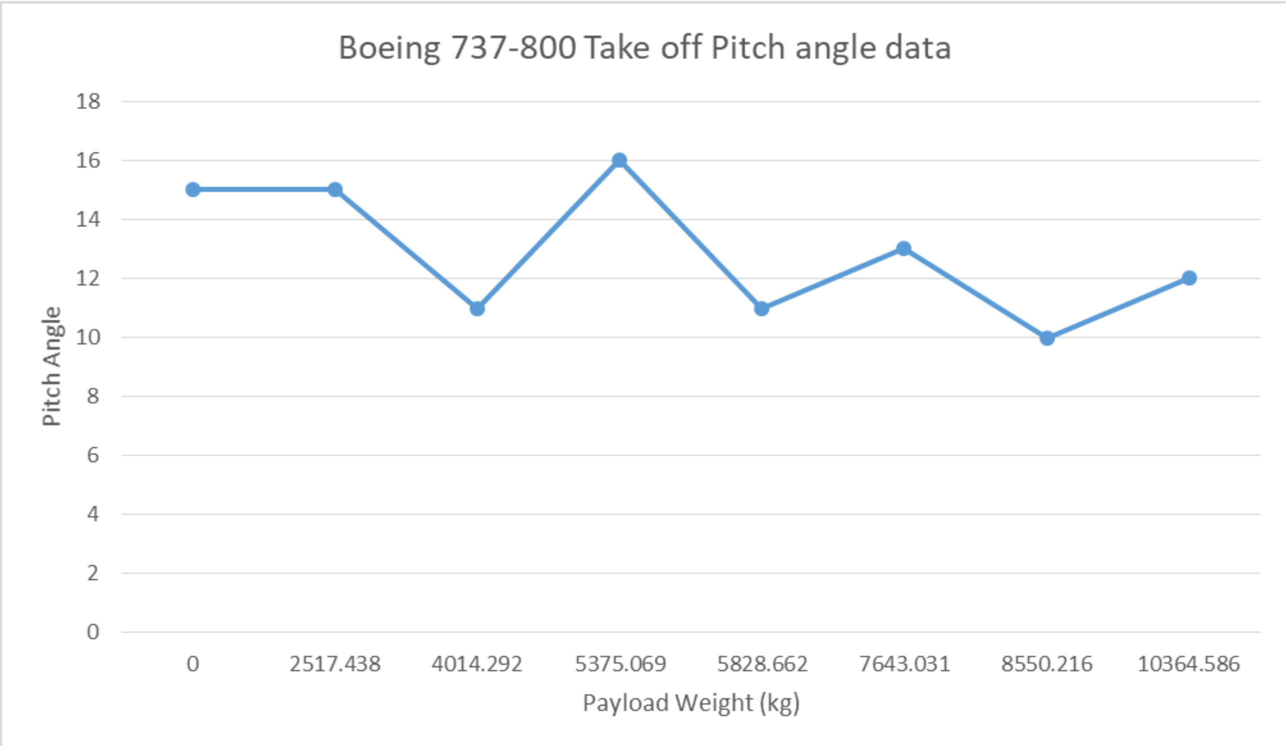
Table 3.1 - Boeing 737-800 Pitch angle behavior test inputs

1.	**2. Weight(kg)**	**3. Trim**	**4. Flaps**	**5. V1(knots)**	**6. Vr(knots)**	**7. Angle**
8. Payload	**9. Fuel**	**10.**	**11.**	**12.**	**13.**	**14.**
15. 0	16. 20762.736	17. +1.8	18. 15	19. 180	20. 190	21. 15+
22. 2517.438	23. 20762.736	24. +1.8	25. 15	26. 129	27. 135	28. 15+
29. 4014.292	30. 20762.736	31. +1.8	32. 15	33. 130	34. 139	35. 11+
36. 5375.069	37. 20762.736	38. +1.8	39. 15	40. 130	41. 138	42. 16+

43. 5828.662	44. 20762.736	45. +1.8	46. 15	47. 132	48. 138	49. 11+
50. 7643.0314	51. 20762.736	52. +1.8	53. 15	54. 145	55. 156	56. 13+
57. 8550.216	58. 20762.736	59. +1.8	60. 15	61. 135	62. 145	63. 10+
64. 10364.586	65. 20762.736	66. +1.8	67. 15	68. 145	69. 154	70. 12+

With the constant maximum fuel load, Boeing 737-800 shows the following variation between the payload weight and the pitch angle.

Graph 3.1.1 - Boeing 737-800 Take off-pitch angle data



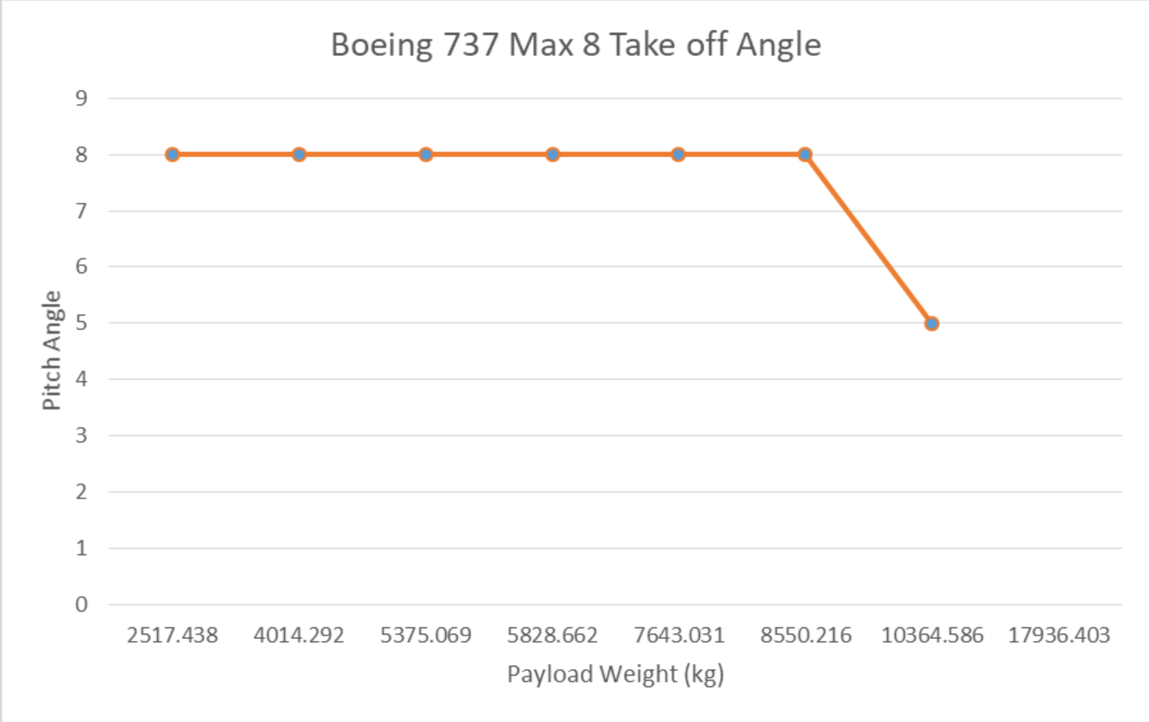
Conclusion 3.1.1 - The maximum pitch angle is reached at the payload of 5375.069 kg s.
The full payload of the aircraft is 10364.586 kg therefore according to the above data the maximum takeoff pitch angle is reached at 51.8599% of its payload. (With max fuel load).It is approximately 52%.

3.1.2. Boeing 737 Max 8 take-off angle data
Flaps 15 *Elevator* 1.8 upward *Fuel weight (At max)* - 20.762Ton *Airline*- Lion Air Boeing 737 Max 8
Flight Number - Test 21 *Time* - 9.30 AM *Whether* - Clear skies
Location - San Francisco International Airport, California, USA
Max Fuel - 20732.8 kg Max payload - 17936.403 kg

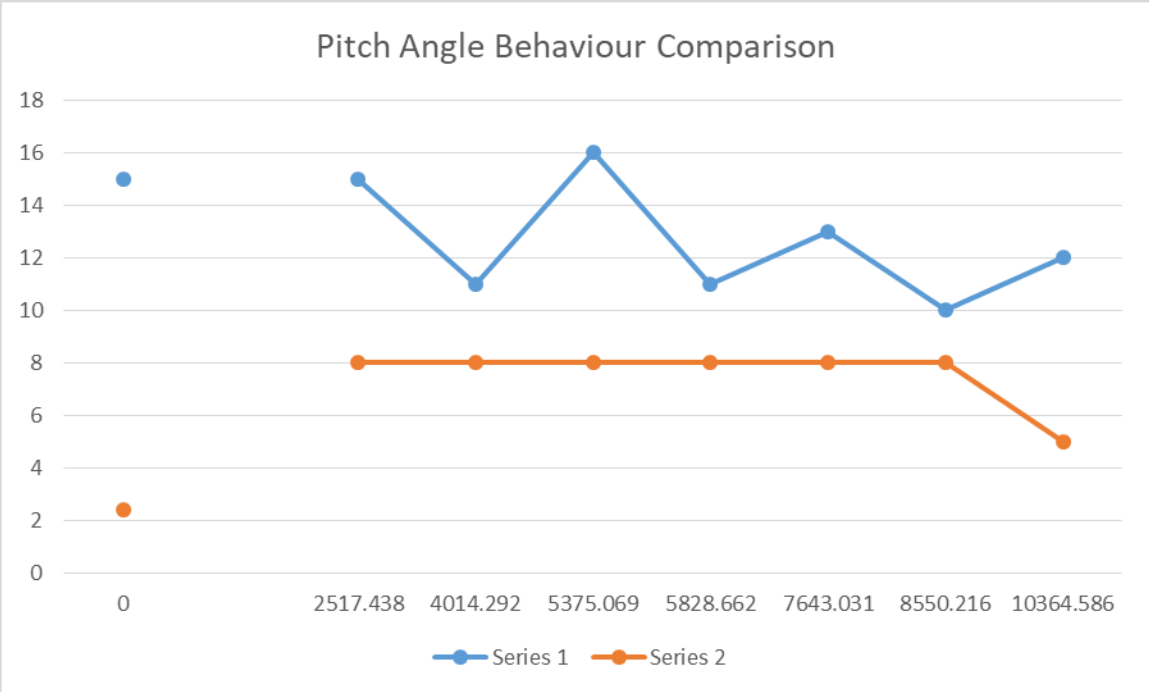
Table 3.2 - Boeing 737 Max 8 pitch angle behavior test inputs

71.	**72. Weight**	**73. Trim**	**74. Flaps**	**75. V1(knots)**	**76. Vr(knots)**	**77. Angle**
78. Payload	**79. Fuel**	**80.**	**81.**	**82.**	**83.**	**84.**
85. 0	86. 20732.8	87. +1.8	88. 15	89. 120	90. 145	91. 8
92. 2517.438	93. 20732.8	94. +1.8	95. 15	96. 118	97. 145	98. 8
99. 4014.292	100. 20732.8	101. +1.8	102. 15	103. 120	104. 148	105. 8
106. 5375.069	107. 20732.8	108. +1.8	109. 15	110. 125	111. 150	112. 8
113. 5828.662	114. 20732.8	115. +1.8	116. 15	117. 130	118. 150	119. 8
120. 7643.0314	121. 20732.8	122. +1.8	123. 15	124. 135	125. 152	126. 8
127. 8550.216	128. 20732.8	129. +1.8	130. 15	131. 135	132. 150	133. 8
134. 10364.586	135. 20732.8	136. +1.8	137. 15	138. 145	139. 160	140. 5+
141. 17936.403	142. 20732.8	143. +1.8	144. 15	145. 145	146. 155	147. 5+

Graph 3.1.2 - Boeing 737 Max8 pitch angle behavior



Graph 3.1.3 - Pitch angle behavior comparison (Boeing737-800 vs. Boeing 737Max8)



According to the above data the pitch angle of the Boeing 737, max 8 appears to be a constant 8 degrees without exceeding the margin of 10 degrees. This situation is extremely dangerous in a practical scenario and can lead to terrible disasters. Therefore the pitch angle of the Boeing 737 max 8, which will give the same pitch angle of the Boeing 737-800 under the same weight conditions should be determined.

3.1.3. Trim Positions

Test method 1 -To determine the elevator trim position of the being 737 Max 8, that will give the same pitch angle of the Boeing 737-800 at the same weight conditions following method is used.

I. Initial conditions were set to Flaps 15, Elevator trims 1.8 upward.
II. Took off normally with the same weather conditions and time from the same airport.
III. Shortly after the takeoff, the elevator trim was gradually increased until it gives the same corresponding take-off angle of the Boeing 737-800 and it was recorded.

Table 3.1.3 **-** Elevator trim position inputs

148. Weight(kg)	149. Boeing 737-800	150.	151. Being 737Max 8	152.
153.	154. Trim	155. Angle	156. Trim	157. Angle
158. 0	159. 1.8	160. 15+	161. 3.4	162. 15+
163. 2517.438	164. 1.8	165. 15+	166. 3.7	167. 15+
168. 4014.292	169. 1.8	170. 11+	171. 3.8	172. 11+
173. 5375.069	174. 1.8	175. 16+	176. 3.6	177. 16+
178. 5828.662	179. 1.8	180. 11+	181. 3.7	182. 11+
183. 7643.0314	184. 1.8	185. 13+	186. 3.5	187. 13+
188. 8550.216	189. 1.8	190. 10+	191. 3.6	192. 10+
193. 10364.586	194. 1.8	195. 12+	196. 3.9	197. 12+

According to the above test results, the average elevator trim positions for various weight conditions of both aircraft are as follows.

Boeing 737-800 - 1.8 upward position
Boeing 737Max8- 3.6 upward position

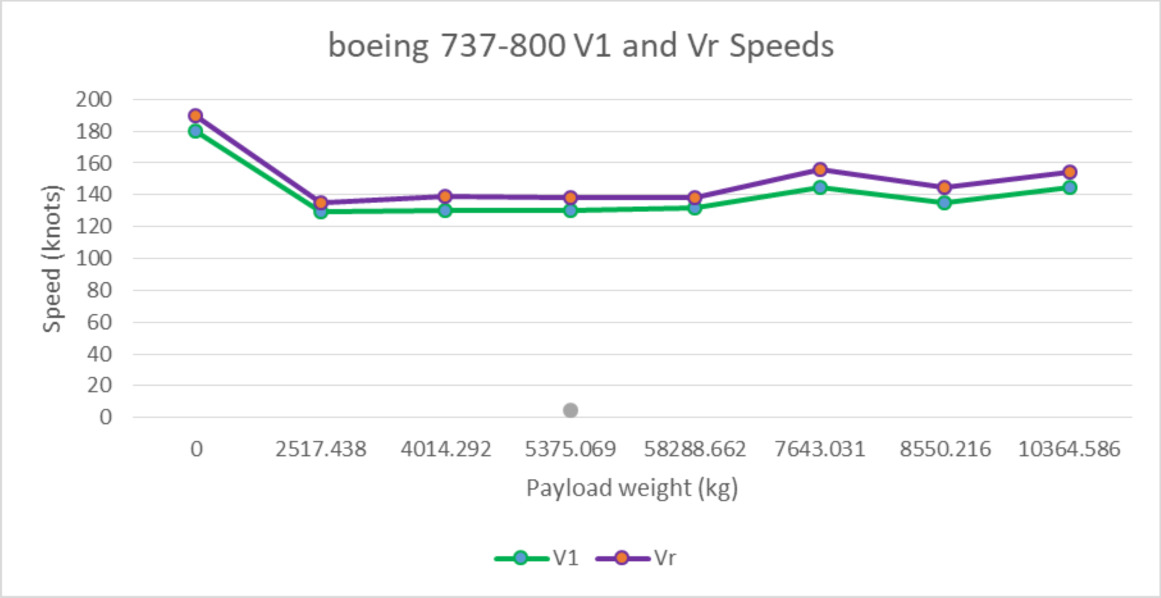
Well, it reveals that the Boeing 737Max8 is demanding double the amount of the elevator pitch trim, then the Boeing 737-800 to provide the same climbing angle under the equal weight conditions.

3.1.4. V1 and V2 Speeds

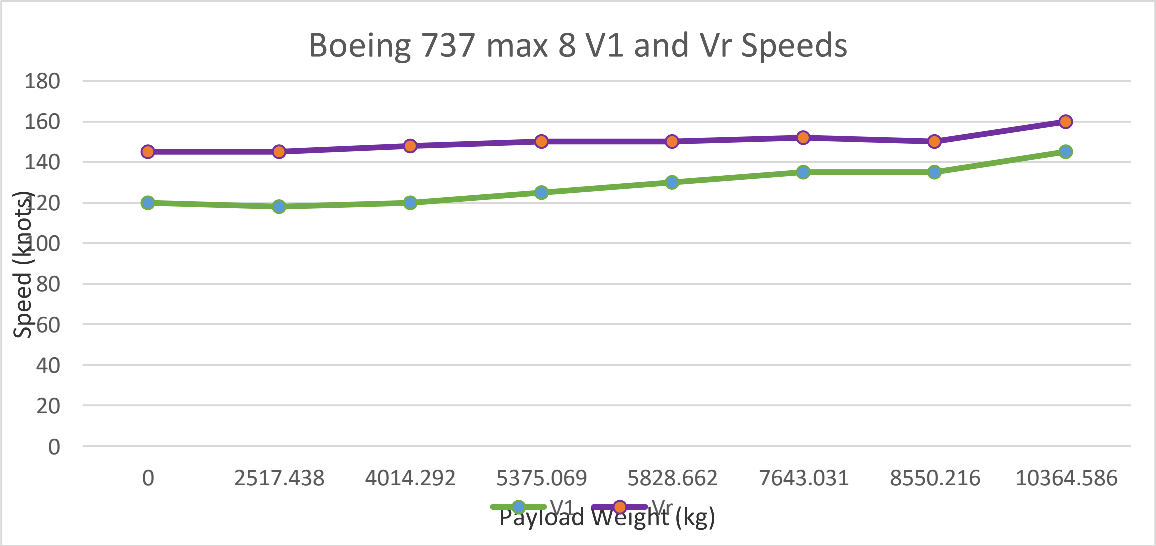
The V1 speed and the Vr speed are giving approximately close values in the Boeing 737-800 and they are reducing when the payload is reducing. But in Max 8 the V1 speed is the only one reducing with the weight and the Vr speed is changing slightly.

Boeing 737-800 V1 and Vr

Graph 3.1.4 - V1 and V2 speeds comparison of Boeing 737-800



Boeing 737 Max 8 V1 and Vr speeds
Graph 3.1.5 - V1 and V2 speeds comparison of Boeing 737 Max 8



According to the above comparison Boeing 737, max 8 is having an increased difference between the V1 and V2 speeds at low weight conditions.

Conclusions 3.1.2
01. Boeing 737 - 800 is giving smooth take-off angles under all weight conditions, with less trimming.
Boeing 737Max 8 gives the same take-off angles under the same equal weight conditions with double the trimming needed for Boeing 737-800.

02. Boeing 737 -800 is having close values in the V1 and Vr speeds, in various weights. And the difference between the two values is almost constant.
Boeing 737Max 8 is having close values in V1 and Vr speeds under heavy payloads and the difference between them tends to tend to be increased when the payload is reducing.

3.2. Stall margin and coffin corner Analysis of Boeing 737-800 and Boeing 737 max 8
The test was conducted at a virtual height of 10000ft s above the mean sea level. And according to the standard commercial aviation rules, the airspeed corresponding to that height is 250 knots.
And to make the aircraft into the stall position the throttle was reduced to a fixed 40% position.

3.2.1. Boeing 737-800 Stall margin analysis

Table 3.2.1 - Boeing 737-800 stall simulation

198. Weight	199. Speed before stall 200. (knots)	201. Time is taken to Stall 202. (seconds)	203. Angle 204. (degrees)
205. 0	206. 250	207. 19.69	208. vertical turn around reaches 70(110)
209. 2517.438	210. 250	211. 20.12	212. vertical turn around reaches 85(95)
213. 4014.292	214. 250	215. 23.85	216. 70
217. 5375.069	218. 250	219. 23.07	220. vertical turn around reaches 80(100)
221. 5828.662	222. 250	223. 27.37	224. 75
225. 7643.0314	226. 250	227. 25.29	228. 52
229. 8550.216	230. 250	231. 35.21	232. vertical turn around reaches to 85(95)
233. 10364.586	234. 250	235. 20.12	236. 60

Considering the above data the average time taken for a Boeing 737-800 to stall is 24.34 seconds. And the average stalling angle of the Boeing 737-800 is 82.125 degrees positive pitch.

3.2.2. Boeing 737 Max 8 stall margin analysis.

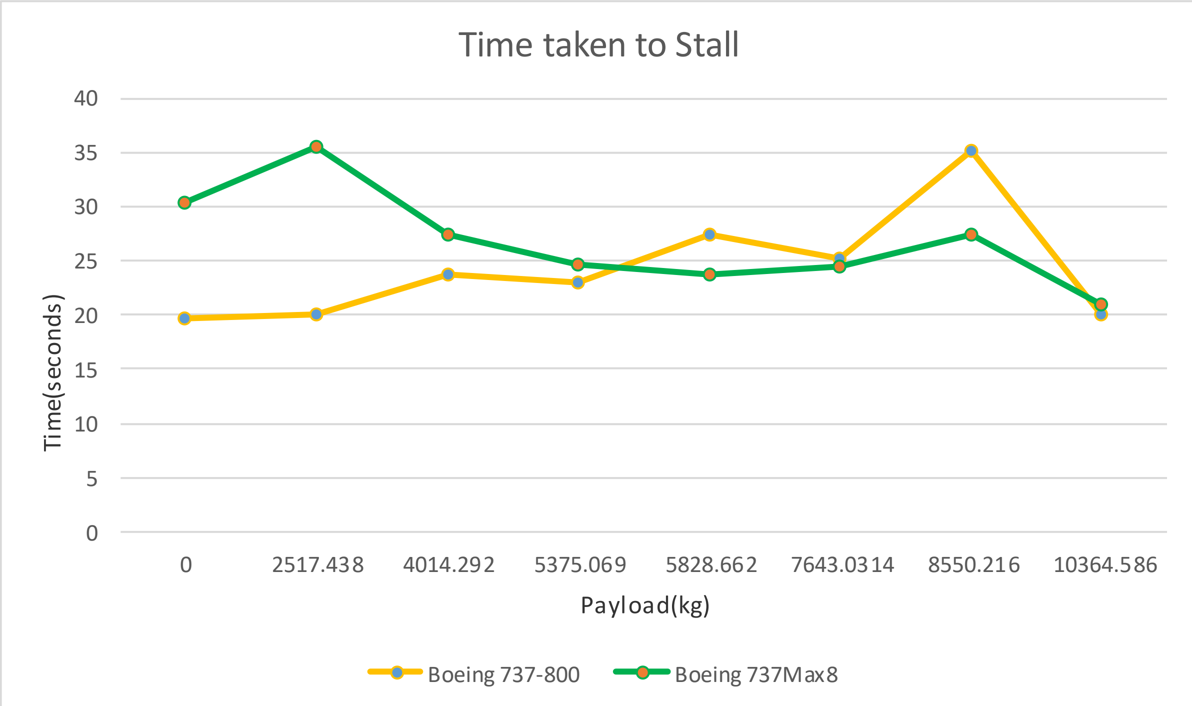
Table 3.2.2 - Boeing 737 Max 8 stall simulation

237. Weight	238. Speed before Stall 239. (knots)	240. Time is taken for stall 241. (seconds)	242. Angle 243. (degrees)
244. 0	245. 250	246. 30.44	247. 88
248. 2517.438	249. 250	250. 35.62	251. 87
252. 4014.292	253. 250	254. 27.40	255. 90 close to vertical turn over(90)
256. 5375.069	257. 250	258. 24.73	259. vertical turn over(90)
260. 5828.662	261. 250	262. 23.79	263. vertical turn over(90)
264. 7643.0314	265. 250	266. 24.56	267. 85
268. 8550.216	269. 250	270. 27.45	271. 75
272. 10364.586	273. 250	274. 20.98	275. 70

According to the above data, it takes an average time of 26.871 seconds for a Boeing 737 Max 8 to become the stall position. And the average stall angle for Boeing 737 Max 8 is 84.375 degrees positive pitch.

Conclusion 3.2.1
When analyzing the stall data of the 737-800 the aircraft is showing an average stall angle of 82.125 degrees and 24.34seconds of time for a stall at the speed of 250 in 1000fts.Boeing 737 Max 8 shows an average stall angle of 84.375 degrees with 26.871seconds to reach the stall point at 250 knots in 1000fts.

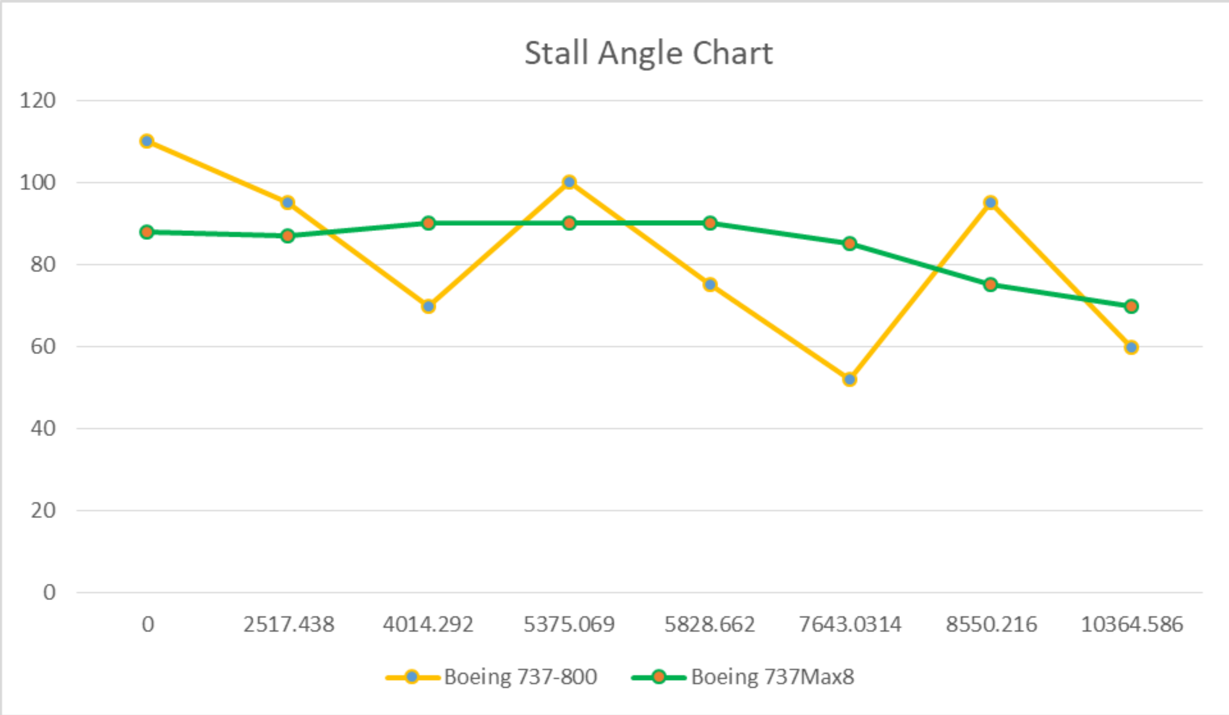
Graph 3.2.1- Boeing 737-800 and Boeing 737 max 8 stall time comparison



Conclusion 3.2.2

According to the above stall time charts, the Boeing 737-800 takes less time to stall in lower weight conditions than in heavy payloads. On the other hand Boeing 737, Max 8 is taking more time to stall at lower weights than in heavyweight conditions. This shows an inverse relationship between the two aircraft variants, concerning the stalling time.

Graph 3.2.2 - Boeing 737-800 and Boeing 737 Max 8 stall angle comparison.



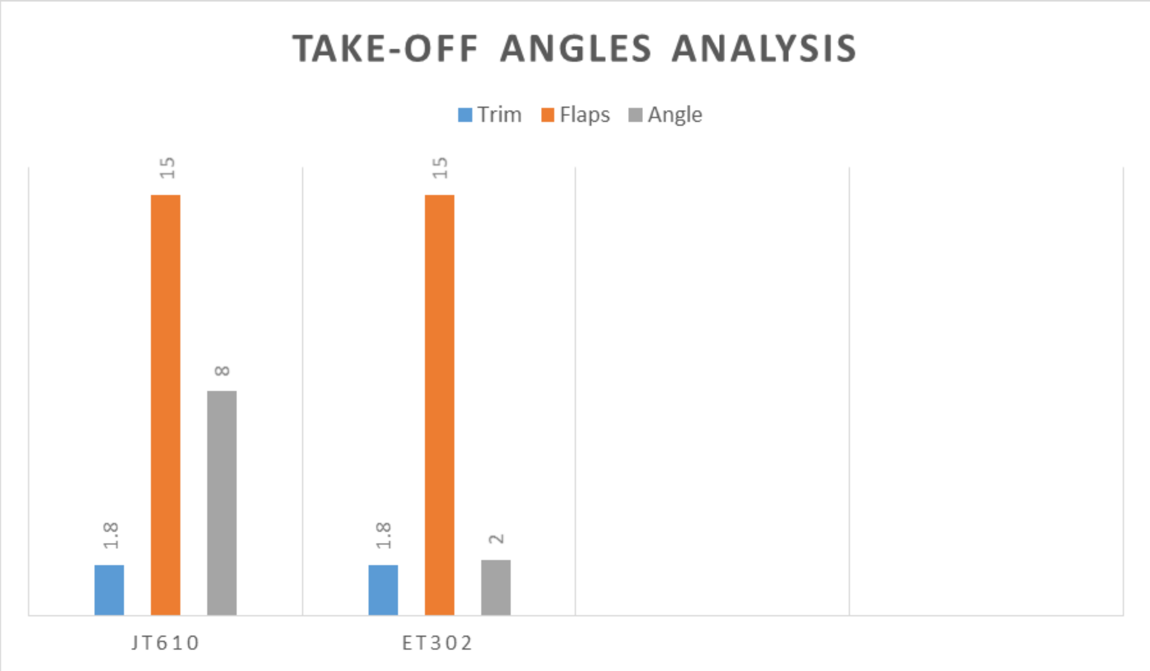
According to the results obtained in the simulation tests regarding the takeoff angle data and thrust levels of Boeing 737, Max 8 the JT610, and ET302 need to show the following angles and trim positions.
Note - The weights of each flight are taken as the average weight of the aircraft during the period of the crash and the flaps are considered to be a standard level of flaps levels of Max 8.
Thrust levels are relatively considered for the average value of the max 8 thrust levels.

Table 3.2.3 - Simulated trim positions and pitch angles of JT610 and ET302

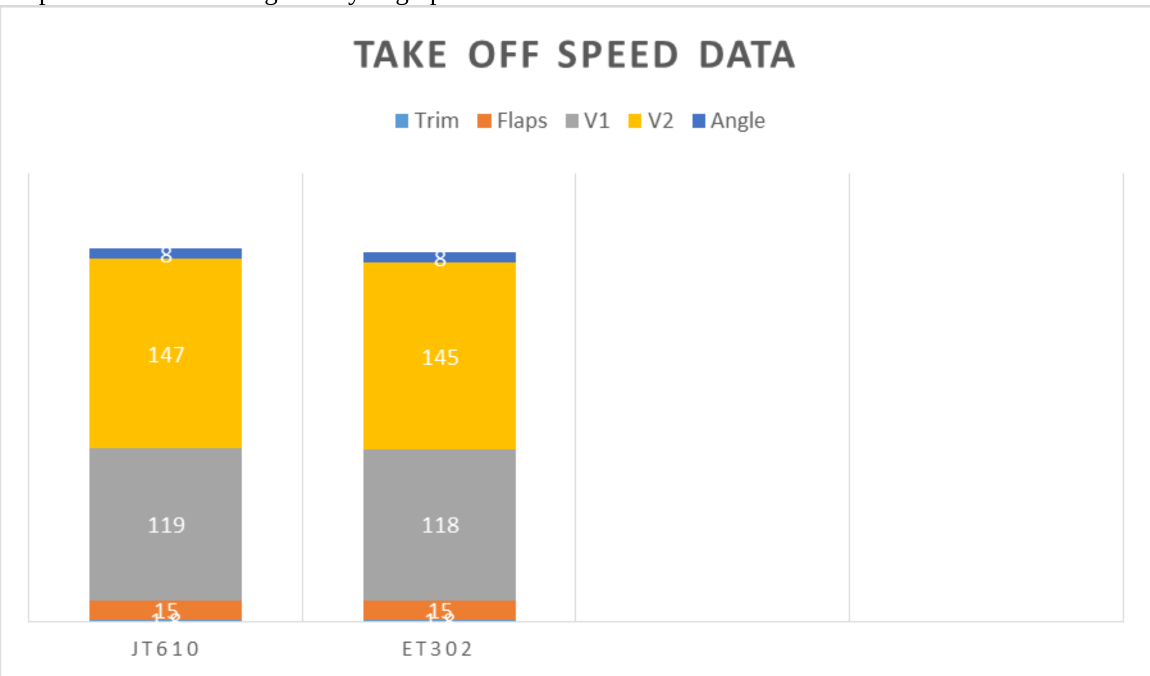
276. Flight	**277. Weight 278. (Payload + Fuel load)**	**279. Trim**	**280. Flaps**	**281. V1 282. (knots)**	**283. Vr 284. (knots)**	**285. Angle 286. (Degrees)**
287. JT610	288. 29,677.05 kg	289. +1.8	290. 15	291. 119	292. 147	293. 8
294. ET302	295. 25,709.47 kg	296. +1.8	297. 15	298. 118	299. 145	300. 8

According to the above analysis, both JT610 and ET302 are showing almost the same results, even though they are having a significant weight difference of nearly 3967.58 kg.

Graph 3.2.3 -Take off the angle analysis graph of JT610 and ET302.



Graph 3.2.4 - take-off angle analysis graph of JT610 and ET302



Conclusion 3.2.3

The JT610 and ET302 showed almost the same takeoff angles when taking off. The takeoff speed of the two aircraft was different from each other only from 1-2 knots. All physical conditions affecting both flights had equal magnitudes up to the accuracy level of plus or minus 2 knots. This means that any effect that each aircraft experienced due to activation of MCAS or any issue in midflight, can be considered to be experienced by the other aircraft.

Now in project objective 3 there is clearly mentioned that the MCAS to be active the AOA should be high and the aircraft should be steeply turning. So according to the investigation results of FAA and NTSB to be MCAS to activate there should be a high AOA (Angle of Attack) in the flight pattern. To check this effect the stall margin analysis of the Max8 should be considered, that is done in the project objective 2 to find out the correct stall margins for the weights regarding each aircraft.

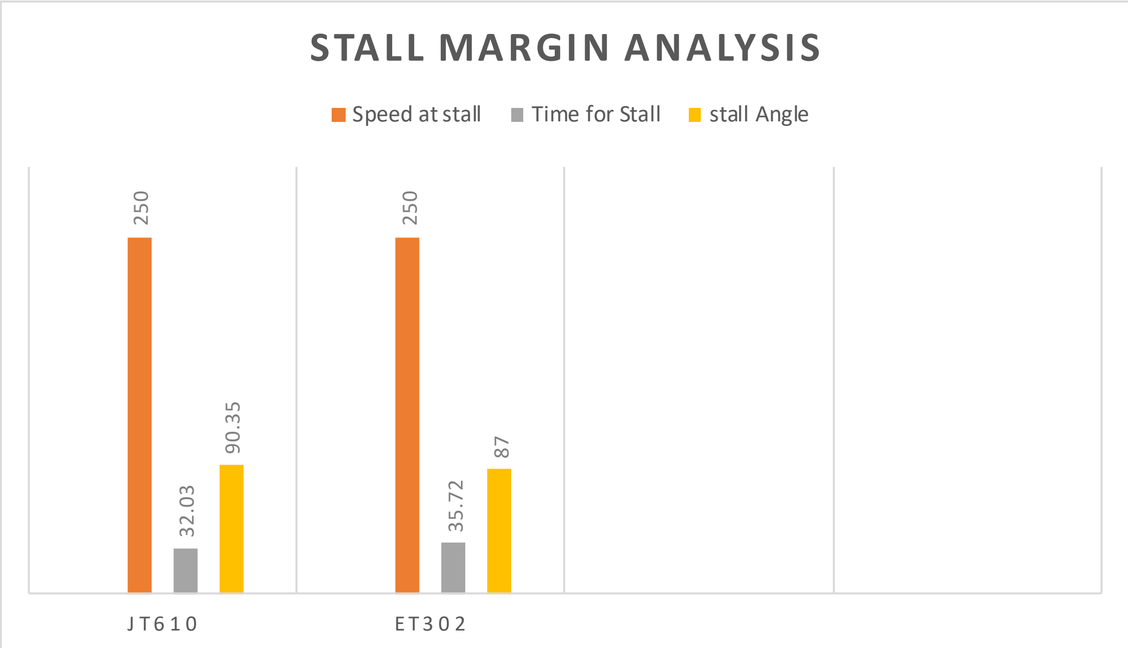
Table 3.2.4 - Stall simulation of JT610 and ET302

301. Flight	**302. Weight(kg)**	**303. Speed at stall 304. (knots)**	**305. Time for stall 306. (seconds)**	**307. The angle at the stall. 308. (degrees)**
309. JT610	310. 29,677.05 kg	311. 250	312. 32.03	313. 90.35(vertical turn over)
314. ET302	315. 25,709.47 kg	316. 250	317. 35.72	318. 87

According to the above-simulated results, both aircraft are reaching the stall margin with a time difference of 3.69 seconds and the important thing is that there is a stall angle difference of 3.37 degrees of stall angle difference.

But that 3.37 degrees difference is extremely deadly because the JT 610 is reaching and exceeding the vertical turn over the point of solid 90 degrees angle for the horizon. And this means that the aircraft is exceeding its final hopes of recovering from the stall and driving into the region of total control loss.

Graph 3.2.5 - Stall margin analysis graph of JT610 and ET302



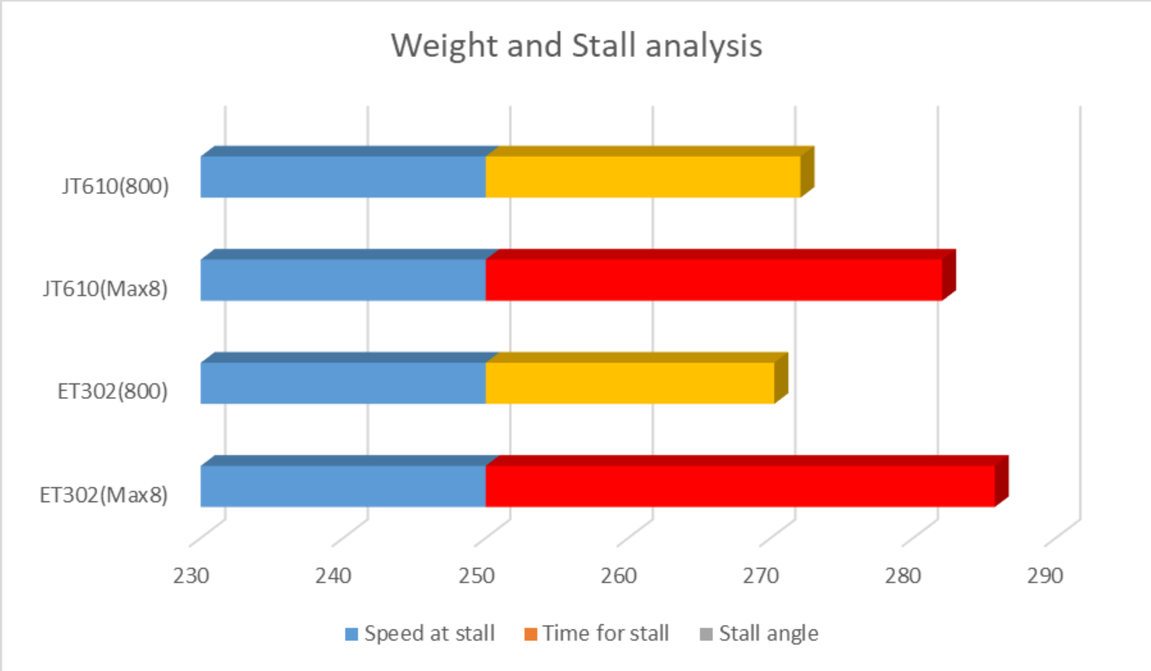
But if we assume that the JT610 and ET302 are Boeing 737-800 aircraft instead of MAX8 s, then the following table shows the simulated data of each aircraft regarding each weight.

Table 3.2.5- Stall simulation of JT610 and ET302 as Boeing 737-800

319. Flight	**320. Weight(kg)**	**321. Speed at stall 322. (knots)**	**323. Time for stall 324. (seconds)**	**325. The angle at the stall. 326. (degrees)**
327. JT610	328. 29,677.05 kg	329. 250	330. 22.09	331. 85(vertical turn over)
332. ET302	333. 25,709.47 kg	334. 250	335. 20.25	336. Vertical turn-over reaches to 84 degrees

Here an important point can be observed that when the load is increasing the time for the stall is also increasing. And that is something that can be observed with an inverse relationship to the data in the MAX 8. The analysis conducted with both conclusions considering the Jt610 and ET302 as MAX8 and 737-800 are plotted in a graph below.

Graph 3.2.6 - Complete weight and stall analysis graph



Conclusion 3.2.4
According to the above data that there is a piece of clear evidence proving that, the JT610 and ET302 pilots had more time to react and counteract to any situation or an issue that could have happened with leading to the point of a stall (coffin corner), than a Boeing 737-800 pilot.
And Boeing 737-800 has increased time to stall when the load is increasing. (Positive correlation).
The Boeing 737Max8 has reduced stall times when the load is increasing. (Negative Correlation).

4. Conclusions

The maximum pitch angle of the Boring 737-800 is reaching at the payload of 5375.069 kg sit is 52% of the total payload of the aircraft. The pitch angle at take-off in Boeing 737 max 8 appears to be a constant 8 degrees without exceeding the margin of 10 degrees. Boeing 737Max8 is demanding double the amount of the elevator pitch trim, then the Boeing 737-800 to provide the same climbing angle under the equal weight conditions.
The V1 speed and the Vr speed are giving approximately close values in the Boeing 737-800 and they are reducing when the payload is reducing. But in Max 8 the V1 speed is the only one reducing with the weight and the Vr speed is changing slightly.
Boeing 737 - 800 is giving smooth take-off angles under all weight conditions, with less trimming. Boeing 737Max 8 gives the same take-off angles under the same equal weight conditions with double the trimming needed for Boeing 737-800.
Boeing 737 -800 is having close values in the V1 and Vr speeds, in various weights. And the difference between the two values is almost constant. Boeing 737Max 8 is having close values in V1 and Vr speeds

under heavy payloads and the difference between them tends to tend to be increased when the payload is reducing.
According to the stall time charts, the Boeing 737-800 takes less time to stall in lower weight conditions than in heavy payloads. On the other hand Boeing 737, Max 8 is taking more time to stall at lower weights than in heavy-weight conditions. This shows an inverse relationship between the two aircraft variants, concerning the stalling time.
Boeing 737MAX 8 has a stable and constant value for the stall angle at given conditions while in Boeing 737-800 has a varying value to the stall angle.
According to the simulations and secondary data, The JT610 and ET302 showed almost the same takeoff angles when taking off. The takeoff speed of the two aircraft was different from each other only from 1-2 knots. All physical conditions affecting both flights had equal magnitudes up to the accuracy level of plus or minus 2 knots.
JT610 and ET302 pilots had more time to react and counteract to any situation or an issue that could have happened with leading to the point of a stall (coffin corner), than a Boeing 737-800 pilot.
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