Analysis and Optimization of Baseline Single Aisle Aircraft for Future Electrified Powertrain Flight Demonstrator Comparisons

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The purpose of this study is to provide baseline single-aisle vehicles for future comparisons with NASA's Electrified Powertrain Flight Demonstrator (EPFD) turbofan powered Vision Systems. Both a large single-aisle (roughly 150 passenger) and a small single-aisle (roughly 100 passenger) vehicle will be separately analyzed using both NASA's General Aviation Synthesis Program and a modernized Python-based version of this program that enables efficient gradient-based optimization of both the airframe and propulsion that currently is being referred to as GASPy. A technology build-up will be conducted to bring the current State-of-the-art vehicles to a projected 2035 technology level by incorporating estimations for improvements in aerodynamics, structures, and propulsions. These vehicles can be used in NASA's future EPFD project as baselines to measure the benefits of future hybrid and fully electric aircraft against. The advanced, large single-aisle will then be used to demonstrate the benefits of a coupled engine-airframe optimization for fuel burn reduction.

Introduction

NASA has actively been developing Electric Aircraft Propulsion (EAP) which combines traditional fuel-based engines with electric motors as potential viable options to meet NASA's aggressive year 2035+ targeted metrics for the projected subsonic transport vehicles relative to current performance. These performance goals are summarized in NASA's 2019 Aeronautics Strategic Implementation Plan document, and shown in Table 1 [1] which show target dates and performance levels for demonstrating the readiness of technologies advanced enough to enable initial application in commercial aircraft.

Table 1. NASA Targeted Improvements in Subsonic Transport System-level Metrics

TECHNOLOGY BENEFITS	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near term 2015-2025	Mid term 2025-2035	Far term Beyond 2035
Noise (cumulative below Stage 4)	22 - 32 dB	32 - 42 dB	42 - 52 dB
LTO NO_x Emissions (below CAEP 6)	70 - 75%	80%	>80%
Cruise NO_x Emissions (relative to 2005 best in class)	65 - 70%	80%	>80%
Aircraft Fuel/Energy Consumption (relative to 2005 best in class)	40 - 50%	50 - 60%	60 - 80%

To estimate the benefits of using EAP in the year 2035+ time frame for NASA's Electrified Powertrain Flight Demonstrators (EPFD) turbofan Vision Systems, it is important to establish a set of baseline non-electrified vehicle performance models for future comparisons. Towards achieving this, the current paper provides a summary of a large single-aisle (roughly 150 passenger) and a small single-aisle (roughly 100 passenger) vehicle generated using NASA's General Aviation Synthesis Program (GASP) [2]. In addition, this paper will utilize a modernized python-based version of the GASP program that enables gradient based optimization referred to as GASPy [3] to demonstrate a coupled airframe and propulsion optimization which will be valuable in future EAP assessments.

Modeling Approach

Analysis of the baseline vehicles have been conducted using both GASP and GASPy. GASP is an aircraft synthesis code, written in FORTRAN that was developed at NASA Ames in the 1970s. The code was later enhanced at Georgia Tech in the 1990s. It uses engineering level analysis to perform vehicle sizing and provide an estimate of the vehicle's performance characteristics appropriate for the conceptual design phase. GASPy is a Python rewrite of GASP in the openMDAO [4,5] environment and was developed without proprietary data tables in order to be made publicly available in the future to the community. There are several advantages to building GASPy in the openMDAO environment; most notable is that analytic derivatives are available to the optimizer enabling high degree-of-freedom optimizations by taking advantage of analytic derivatives. Another benefit is the ease with which other disciplines can be integrated, such as propulsions modeling with pyCycle [6] which is a thermodynamic cycle modeling library that was designed to model engine performance and is based on NASA's Numerical Propulsion System Simulation (NPSS) software. The pyCycle software was integrated into GASPy to allow the engine to be optimized along with the airframe.

Using the state-of-the-art (SOTA) vehicle models, advanced technologies were incrementally added to represent an advanced tube and wing vehicles with an entry into service of approximately 2035. Technology factors were applied to account for advanced composites, aerodynamic improvements, and advanced geared turbofans. The advanced vehicles can be used as baselines for the more novel concepts that are expected to be developed through the course of NASA's EPFD project. Additionally, the sensitivity to changes in technology can provide information about which areas are important to focus on for both risk reduction and technology development.

The paper will then include the results of a study of an airframe-engine optimization using GASPy based on the nominal advanced 737 MAX 8. Throughout the optimization, design range, cruise Mach number, passenger count, and technology levels will be held constant. The wing's aspect ratio and sweep, the engine's fan pressure ratio, and the start of cruise altitude will be allowed to change by serving as design variables. For the sake of simplicity, and to align with the EPFD goals, mission block fuel will be used as the merit function to be optimized. In the future, noise, NO_x emissions, life-cycle cost will also be included as part of future vehicle comparisons but will not be included in this paper.

Establishing and optimizing baseline vehicles for a particular entry into service is beneficial for the EPFD project because it will ensure that any predicted benefit of future electrified aircraft can be properly attributed to Electrified Aircraft Propulsion (EAP) and not simply a result of a delayed entry into service that takes advantage of technological developments that would also benefit a conventional tube and wing aircraft at that time.

Reference Turbofan Vehicles and Calibration of Vehicle Models

Two existing turbofan vehicles were chosen for baselining. The Boeing 737 Max 8 was chosen as the state-of-the-art large single-aisle aircraft. The B737 Max 8 can carry 156 passengers for a design range of 3,675 nautical miles. The E190-E2 regional jet will be used as the state-of-the-art for a small single-aisle aircraft. The E190-E2 can carry 104 passengers and has a design range of 3,380 nautical miles. These vehicles have been compared to, and calibrated against, available data. Performance data and a detailed weight breakdown will provide the primary metrics that will be assessed to check the accuracy of our baseline models.

Table 2. Summary of Baseline Aircraft

	Boeing 737 MAX 8	Embraer E190-E2
MTOW (lbf)	176,254	124,341
Engine	CFM LEAP-1B	PW1922G
Thrust (lbf/engine)	28,928	23,800
Cruise Mach	0.8	0.78
Cruise Altitude (ft)	35,000	35,000
Design Range (NM)	3,675	3,380
Passengers	156	104

Boeing 737 Max 8

Using the payload-range diagram provided by the Boeing 737 Max 8's Airport Planning Manual (APM) [7] as shown in Figure 1, and assuming that all 189 seats are filled, we are able to approximate the maximum range for a mission and the fuel required. A GASP model of the 737 MAX 8 was then developed for a 2,900 nautical mile mission with 189 passengers.

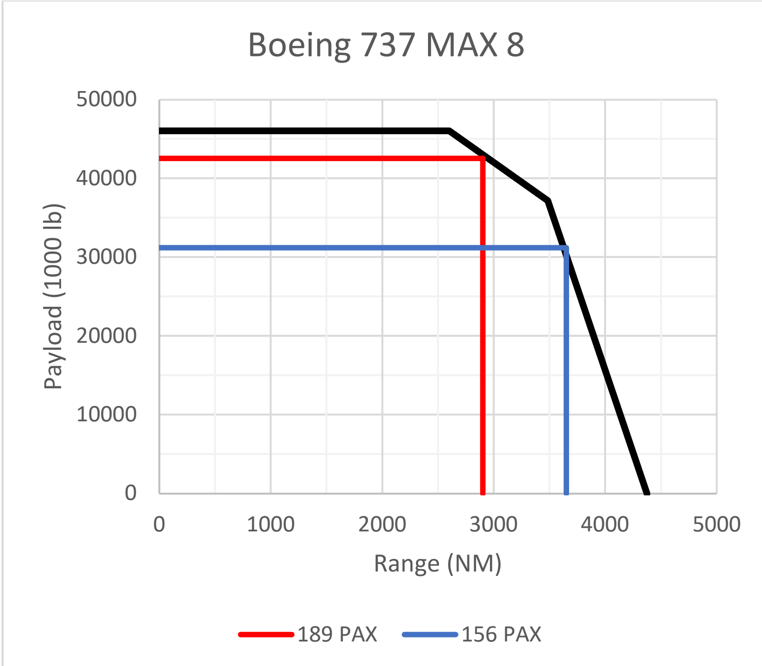

Figure 1. Boeing 737 MAX 8 Payload-Range Diagram [7]

Comparison of the closed GASP model closely matched Boeing's reported values to within 1.25% as shown in Table 3 below. This provided confidence in our modelling method and allowed us to proceed with modeling the vehicle in GASPy.

Table 3. Boeing 737 Max 8 Key Characteristics

737 MAX 8	APM [7]	GASP	% Diff
GTOW (lbf.)	182,200	181,700	0.27%
Fuel Weight (lbf.)	40,315	39,814	1.24%
Range (NM)	2900	2885	0.52%
Wingspan (ft.)	117.83	117.4	0.36%
Fuselage Length (ft.)	128.25	128.4	-0.12%
SLS Thrust (lbf./engine)	28,690	28,690	0%

Table 4 provides a comparison of the GASP weight breakdown in pounds (lbs.) to the GASPy results to validate the new method which shows excellent agreement to within 2% differences. Details of validation of the GASPy software to GASP for the 737 MAX 8 can be found in reference 3. Note that the mission being analyzed here is different from the mission chosen from the APM. In this case, the mission being flown by both GASP and GASPy is 3,675 nautical miles while carrying 156 passengers.

Table 4. Baseline 737 Weight Breakdown

System (lbf.)	GASP	GASPy	% Diff
Propulsion Group	**15736**	**15734**	**0.01**
Primary engines	12260	12260	0.00

Engine Installation	1716	1716	0.00
Fuel System	1760	1758	0.11
Structures Group	**50968**	**50568**	**0.78**
Wing	16059	16013	0.29
Horizontal Tail	2323	2275	2.07
Vertical Tail	2326	2297	1.25
Fuselage	19066	18801	1.39
Landing Gear	7506	7487	0.25
Engine Section	3689	3694	-0.14
Flight Controls Group	**3916**	**3906**	**0.26**
Fixed Equipment	**21167**	**21088**	**0.37**
Empty Weight	**91787**	**91296**	**0.53**
Fixed Useful Load	**5089**	**5168**	**-1.55**
Mission Block Fuel	**42928**	**42871**	**0.13**
Payload	**35100**	**35100**	**0.00**
Gross TO Weight	**174904**	**174434**	**0.27**

Embraer E190-E2

The same validation and calibration process was used for the smaller E190-E2 vehicle. Using the payload-range diagram provided by the E190-E2 APM [8] as shown in **Error! Reference source not found.**, when all 104 seats of the E190-E2 are filled, the range and fuel consumed can be approximated.

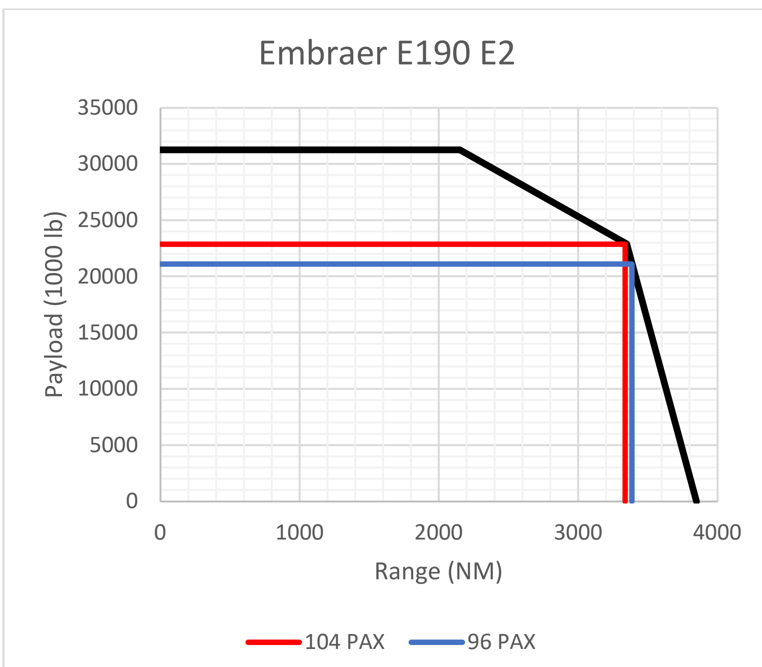

Figure 2. Embraer E190-E2 Payload-Range Diagram [8]

Again, the GASP model of the E190-E2 closely matches the values reported by Embraer in the APM to within 3% as shown in Table 3 below.

Table 5. Embraer E190-E2 Key Characteristics

E190-E2	APM [8]	GASP	% Diff
GTOW (lbf.)	124,341	124,445	-0.08%
Fuel Weight (lbf.)	29,760	30,654	-3.00%
Range (NM)	3350	3385	-1.04%
Wingspan (ft.)	110.63	110.6	0.03%
Fuselage Length (ft.)	119.19	119.5	-0.26%
SLS Thrust (lbf./engine)	23,000	23,800	0%

Table 6 contains the comparison of the GASP weight breakdown in pounds (lbs.) to the GASPy results for the E190-E2 and these show good agreement to within 3%, except for the flight control group which is 4.56%. However, this only a 129-pound difference out of the gross takeoff weight of approximately 124,000 pounds. Similar to the 737 Max 8, an economic mission with a longer range and fewer passengers was evaluated for the comparison of GASP and GASPy.

Table 6. Baseline E190-E2 Weight Breakdown

System	GASP	GASPy	% Diff
Propulsion Group	**12,754**	**12,724**	**0.24**
Primary engines	10,248	10,248	0.00
Engine Installation	1,435	1,435	0.00
Fuel System	1,071	1,041	2.80
Structures Group	**35,672**	**35,142**	**1.49**
Wing	12,776	12,583	1.51
Horizontal Tail	1,716	1,685	1.81
Vertical Tail	940	925	1.60
Fuselage	13,015	12,784	1.77
Landing Gear	4,848	4,789	1.22
Engine Section	2,376	2,375	0.04
Flight Controls Group	**2,827**	**2,698**	**4.56**
Fixed Equipment	**15,901**	**15,848**	**0.33**
Empty Weight	**67,154**	**66,412**	**1.10**
Fixed Useful Load	**3,723**	**3,751**	**-0.75**
Mission Block Fuel	**32,162**	**31,254**	**2.82**
Payload	**21,840**	**21,840**	**0.00**
Gross TO Weight	**124,879**	**123,257**	**1.30**

Advanced Technology Trade Study

To understand the benefits of different advanced technologies to the baseline vehicles, a technology buildup trade study was performed for both reference vehicles. The approximations for improvements in aerodynamic efficiency, material strength, and propulsor designs were then applied to the models based on the assumption shown in Table 7.

Table 7. Advanced Technology Assumptions

Aerodynamics	**Fuselage Profile Drag**	**4% reduction (Expert Opinion)**
	Wing/Tail Profile Drag	**4% reduction (Expert Opinion)**
	Interference Drag	**9% reduction (Expert Opinion)**
Structures	**Structures Weights**	**Aluminum Fuselage: 0% reduction Composite Wing: 26% reduction (PRSEUS Composites) [9]**
	Landing Gear	**0% reduction (Expert Opinion)**
Propulsions	**2035 Engine**	**FPR 1.45 GRC GTF**

Advanced Aerodynamics: Aerodynamic benefits are currently included as a reduction to form factor coefficients in drag calculations. These are approximations of the aggregate benefit from technologies such as active flow control, excrescence reduction, and natural laminar flow.

Advanced Structures: Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) composites [12,13] use built in stringers and stitched interfaces to create seamless transitions and eliminate the need for many joints and fasteners. This results in a structure that is stronger and lighter than traditional composites. Additionally, the damage arresting nature of PRSEUS structures allow them to be designed such that they can continue to operate safely after a failure, similar to current aluminum designs. When designed to function even post buckling, structural weight can be reduced as individual members are allowed to carry higher loads. Conversations with a SME from NASA suggested a 26% weight savings. Because composites are generally more expensive to produce, aircraft fuselages are typically aluminum, as such, PRSEUS weight savings have only been applied to the wing. Currently, there are no revolutionary technologies that are expected to have a significant impact on the design and weight of landing gear on conventional tube and wing aircraft.

Advanced Engines: NASA Glenn Research Center (GRC) provided a family of turbofan engines with a technology level consistent with an entry into service of roughly 2035. The engine family included both geared turbofan (GTF) and direct drive turbofans in a variety of fan pressure ratios. The geared turbofan with a fan pressure ratio (FPR) of 1.45 was selected as the advanced engine that would be used for the advanced 737 and E190. Table 8 shows a comparison of the LEAP-1B engine that is standard on the 737 MAX 8 and the advanced GTF engine.

Table 8. Comparison of LEAP-1B and GRC advanced GTF engine

Engine Parameter	Baseline LEAP-1B	Advanced FPR 1.45
Fan Pressure Ratio	1.45	1.45
Bypass ratio	9.0	15.4
OPR	45	55

$T4_{MAX}$ (°R) STD+27°	3280	3161
SLS Thrust (lb_f)	29,500	28,620
Thrust Lapse (39Kft / Mach 0.80 to SLS)	0.155	0.203
Fan Diameter (in)	69.4	88.3
SLS Airflow (lb/sec)	995	1400
Engine Weight (lbs)	6130	6740
Bare Engine Thrust-to-Weight	4.76	4.25
TSFC@M0.8/39Kft (lb/hr/lb_f)	0.548	0.515

The advanced geared turbofan has a higher bypass ratio and larger fan diameter than the LEAP-1B. Although, it is heavier and has a lower thrust to weight ratio than the baseline, the advanced geared turbofan has better thrust specific fuel consumption. Additionally, the GTF has a lower turbine inlet temperature, which typically corresponds to a longer service life.

Table 9 shows the result of the technology build up for the 737 MAX 8 vehicle based on applying the respective advancements outlined in Table 7.

Table 9. Large Single Aisle Advanced Technology comparison to SOTA

Parameter	SOTA: B737 Max 8 [LEAP 1B]	Advanced: B737 [FPR 1.45 GTF]	% Improved
Gross TO Weight (lbs)	181700	141627	-22.05%
Empty Weight (lbs)	95539	79681	-16.60%
Wing Aspect Ratio	10.13	11	5.59%
Span (ft)	117.8	117.9	0.08%
Wing Loading (psf)	132.6	112.1	-15.46%
Engine SLS Thrust (lb_f)	28690	16981	-40.81%
T.O. T/W	0.316	0.24	-24.05%
Flat Plate Area (ft^2)	27.28	19.9	-27.05%
Cruise Altitude (ft)	35000	37100	6.00%
Cruise CL	0.5804	0.5412	-6.75%
Cruise L/D	18.52	20.6	11.23%
Cruise TSFC (lb_f/hr/lb_f)	0.541	0.5139	-5.01%
Part 25 AEO TOFL (ft)	6203	7063	13.86%
Approach Speed (KEAS)	145.1	137.3	-5.38%
Design Mission Block Fuel (lb)	38510	30323	-21.26%

The weight breakdown of each configuration studied during the technology buildup is shown in Figure 3. Starting with the baseline, each category of technologies was applied individually. An advanced configuration with just structural and aerodynamic improvements was considered as well, to represent a case where advanced engines are either not ready for certification or are prohibitively expensive. Finally, a fully advanced vehicle was considered as well. As was to be expected, the use of advanced composites had the greatest contribution to reducing structural weight. Additionally, the advanced geared turbofan had the greatest effect on fuel savings.

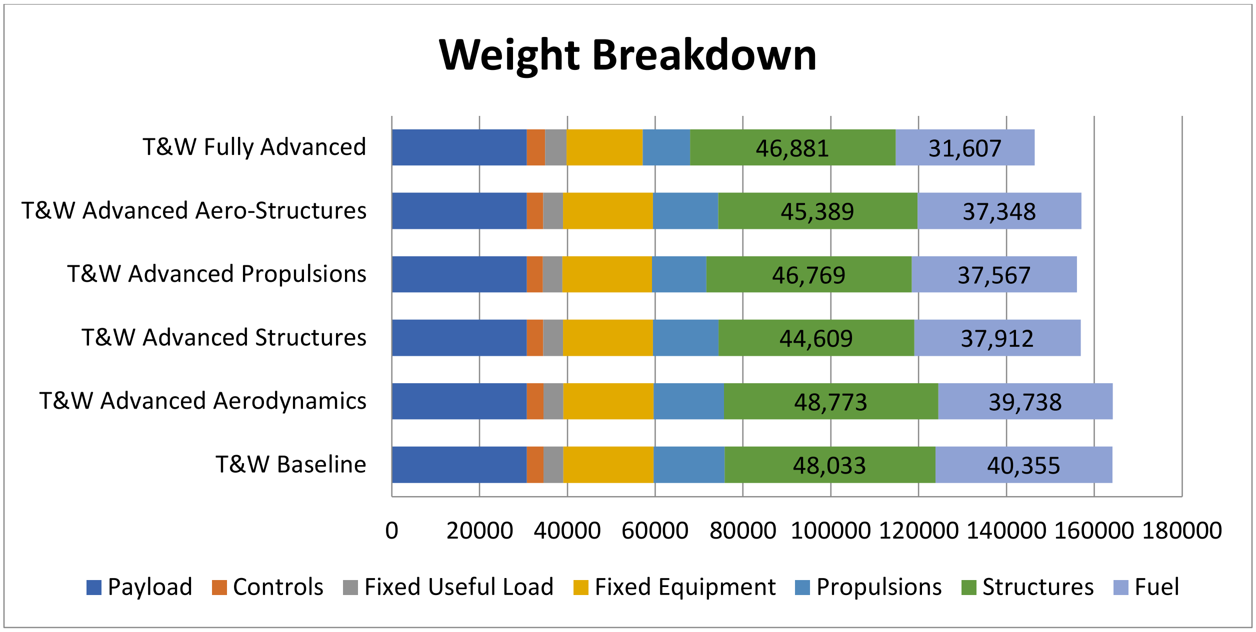

Figure 3. Weight Breakdown from Technology Buildup

Several interesting interactions can be observed from the weight breakdown. First, the advanced aerodynamics reduced fuel burn, but increased structural weight, in both the baseline to aero and structures to aero-structures cases. Additionally, there is a compounding effect on fuel burn when combining all advanced technologies. This is likely caused by a combination of lighter engines, thinner wings, and stiffer structure.

Table 10. Small Single-Aisle Advanced Technology comparison to SOTA

Parameter	SOTA: E190-E2 [PW1922G]	Advanced: E190 [FPR 1.45 GTF]	% Improved
Gross TO Weight (lbs)	124780	113190	-9.29%
Empty Weight (lbs)	66949	60311	-9.92%
Wing Aspect Ratio	11.03	11.03	0.00%
Span (ft)	110.6	110.5	-0.09%
Wing Loading (psf)	112.6	102.2	-9.24%
Engine SLS Thrust (lb_f)	23800	15054	-36.75%
T.O. T/W	0.382	0.133	-65.18%
Flat Plate Area (ft^2)	21.79	20.47	-6.06%
Cruise Altitude (ft)	37000	37000	0.00%
Cruise CL	0.57	0.52	-8.77%
Cruise L/D	18.24	18.53	1.59%

Cruise TSFC (lb_f/hr/lb_f)	0.5429	0.5065	-6.70%
Part 25 AEO TOFL (ft)	5207	7168	37.66%
Approach Speed (KEAS)	140.7	139.2	-1.07%
Design Mission Block Fuel (lb)	30642	25570	-16.55%

Future Work: Before the completion of the final manuscript several important pieces of work will be completed. First, the design missions for the 737 MAX 8 and the E190-E2 will be reanalyzed in GASPy using the same design mission that is represented in the APM. Second, the nominal values for the advanced technologies that are currently based on expert opinion will be replaced with values based on external research. Finally, the coupled engine-airframe optimization will be carried out on the 737 MAX 8.

Conclusions

This study provides a set of baseline single-aisle vehicle models for future comparisons to NASA's Electrified Powertrain Flight Demonstrators turbofan powered Vision Systems. Included are a large single-aisle (roughly 150 passenger) and a small single-aisle (roughly 100 passenger) vehicle generated using NASA's General Aviation Synthesis Program (GASP) and a modernized python-based version of this program that enables gradient based optimization of both the airframe and propulsion referred to as GASPy. For each vehicle class, a technology build-up is applied to bring their current state-of-the-art technology to a projected 2035 time-frame level of advancement by incorporating estimations for improvements in aerodynamics, structures, and propulsions. Analysis was conducted with both the legacy GASP code as well as the new GASPy code. GASPy will also be used to optimize the large single-aisle to demonstrate coupled propulsion-airframe optimization. Future studies that investigate hybrid or fully electric aircraft can use these single-aisle, turbofan aircraft as baselines from which to measure their benefits against.

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