UNIVERSIDADE DE SÃO PAULO
ESCOLA DE ENGENHARIA DE SÃO CARLOS

ALEXANDRE FILGUEIRAS CRUZ

Sistema de Frenagem Regenerativa para Jatos Regionais

São Carlos
2018

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Regenerative braking system for regional jets

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Dissertação de mestrado apresentada ao Programa de Engenharia Mecânica da Escola de Engenharia de São Carlos como parte dos requisites para obtenção do título de Mestre em Ciências.

Área de concentração: Aeronaves

Orientador: Prof. Dr. Fernando Martini Catalano

ESTE EXEMPLAR TRATA-SE DA
VERSÃO CORRIGIDA.
A VERSÃO ORIGINAL ENCONTRA-
SE DISPONÍVEL JUNTO AO
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Eduardo Graziosi Silva - CRB - 8/8907

ALEXANDRE FILGUEIRAS CRUZ

Regenerative braking system for regional jets

Master dissertation submitted to the São Carlos School of Engineering, University of São Paulo, in partial fulfilment of the requirements for the degree of Master of Science in Aeronautical Engineering.

Advisor: Prof. Dr. Fernando Martini Catalano

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ABSTRACT

CRUZ, A. F. **Regenerative braking system for regional jets**. 2018. 62p. Dissertation (Master of Sciences) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2018.

Aircraft brakes are crucial for flight safety and ground operations but are dead weight during every other flight phases. Carbon brake disks are efficient and simple energy accumulators, which transform kinetic energy from landings or rejected take-offs into heat to be later dissipated. Replacing current brakes by electric generators/motors creates additional functions to the systems such as autonomous pushbacks, silent and emission-free taxis, allows reduction of systems as the auxiliary power unit and the ram air turbine and, above all, creates the possibility to input additional thrust during take-off acceleration, which may be asymmetric or not. This research intends to study the impact of installing this system on a regional jet such as Embraer EMB-190 by analyzing its flight operation during takeoff. This arrangement produces a leap on overall performance on short runways, boosting load capacity by 21% while being possible to offset its weight through complete system integration. Regenerative brake systems improvements in performance and parts count reduction are high enough to encourage aircrafts to be redesigned and suggests a path for a new commercial jet generation.

Keywords: Aircraft brakes. Regenerative brakes. Take-off performance. Flight test. Hybrid aircraft.

RESUMO

CRUZ, A. F. **Sistema de Frenagem Regenerativa para Jatos Regionais.** 2018. 62p. Dissertation (Master of Sciences) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2018.

Freios de aeronaves são cruciais para segurança de voo e operações em solo mas também são peso morto em todas as demais fases de voo. Freios com discos de carbono são simples e eficientes acumuladores, transformam energia cinética do pouso ou de decolagens abortadas em calor para posterior dissipação. Substituir estes freios por motores/geradores elétricos cria diversas possibilidades e funções para este sistema como reboques autônomos, taxis silenciosos e sem emissões, redução da necessidade de fontes de energia como APU e RAT e sobretudo, permite adição de energia durante as corridas de decolagem de forma simétrica ou não. Esta pesquisa visa estudar o impacto da instalação deste sistema em uma aeronave Embraer EMB-190 analisando seu desempenho de decolagem. Este novo arranjo produz um salto no desempenho em pistas curtas, elevando a capacidade de carga em 21% enquanto compensa seu peso através de integração de sistemas. O ganho de desempenho e a redução de massa da aeronave, graças ao uso de freios regenerativos, encorajam repensar os projetos atuais e são um caminho para uma noiva geração de jatos regionais. taxiamento autônomo

Palavras chave: Freios de aeronaves. Freios Regenerativos. Desempenho de decolagem. Ensaio em voo, Aeronave híbrida.

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

ABSC – Aircraft Braking Systems Corporation
AIAA – American Institute of Aeronautics and Astronautics
AFM – Airplane Flight Manual
ANAC – Agência Nacional de Aviação Civil
AOG – Aircraft on Ground
APU – Auxiliary Power Unit
CG – Center of Gravity
EASA – European Aviation Safety Agency
FAA – Federal Aviation Authority
FAR – Federal Aviation Regulations
FIA – Federation Internationale de l'Automobile
IEEE – Institute of Electrical and Electronics Engineers
KERS – Kinetic Energy Recovering System
MBE – Maximum Brake Energy
MEL – Minimum Equipment List
MLW – Maximum Landing Weight
MMEL Master Minimum Equipment List
MTOW – Maximum Take-Off Weight
NASA STI – National Aeronautics and Space Administration Scientific and Technical Information
NTSB – National Transportation Safety Board
QRH – Quick Reference HanLdbook
QTA – Quick Turn Around
OEI – One Engine Inoperative
RAT – Ram Air Turbine
RTO – Reject Take-Off
SBRJ – Santos Dumont Airport
ZVEI – Zentralverband Elektrotechnik- und Elektronikindustrie

LIST OF SYMBOLS

A	Ampere
CD	Drag coefficient
CL	Lift coefficient
NiCd	Nickel-cadmium
NiMh	Nickel-metal hydride
kt	knot
kVA	kilo Volt-Ampere
V	Volt
V_{LOF}	Lift-off speed
V_{MC}	Minimum control speed with the critical engine inoperative
V_{MCG}	Minimum control on ground speed
V_R	Rotation speed
V_{REF}	Reference speed
V_S	Speed at which the critical engine is assumed to fail during takeoff
V_1	Decision speed
V_{1min}	Minimum decision speed
V_2	Takeoff safety speed
V_{2min}	Minimum takeoff safety speed

SUMMARY

Motorsport use of KERS motivates the possibility of a similar system for aircrafts as low weight and high energy densities are present on both, even though involved energy levels are much different.

This research focuses on the most demanded commercial aircrafts regarding ground operations: regional jets. Regional jets are commercial transport airplanes characterized by multiple, relatively short-distance, flights - hence, multiple cycles. Generally, regional jets transport 70 to 160 passengers and may cycle up to 14 times a day. That means requiring 14 takeoffs, landings, taxi in and out, pushbacks and all other ground operation, as boarding. For this reason, demand for personnel, ground equipment and extreme coordinated operations are required in order to maintain flight schedules.

Designed by Embraer since 1998 and first flown in 2004, Embraer ERJ-190 is a typical regional jet. This research analyses the viability of installing electric motors/generators instead of carbon disks brakes in this aircraft. Before introduction of lithium batteries, 20 years ago, it would be unimaginable installing extreme power demanded motors/generators and battery banks in aircrafts due to weight penalty.

Such installation creates numerous possibilities for increasing performance at some weight penalty. Differently from electric cars and other vehicles, however, regeneration of brake energy does not intend to increase system efficiency as landing kinetic energy is only one of the many energy source for aircrafts. The proposed system intends to integrate and provide better means of performing ground operation tasks including takeoff and landing.

1.1 Objective

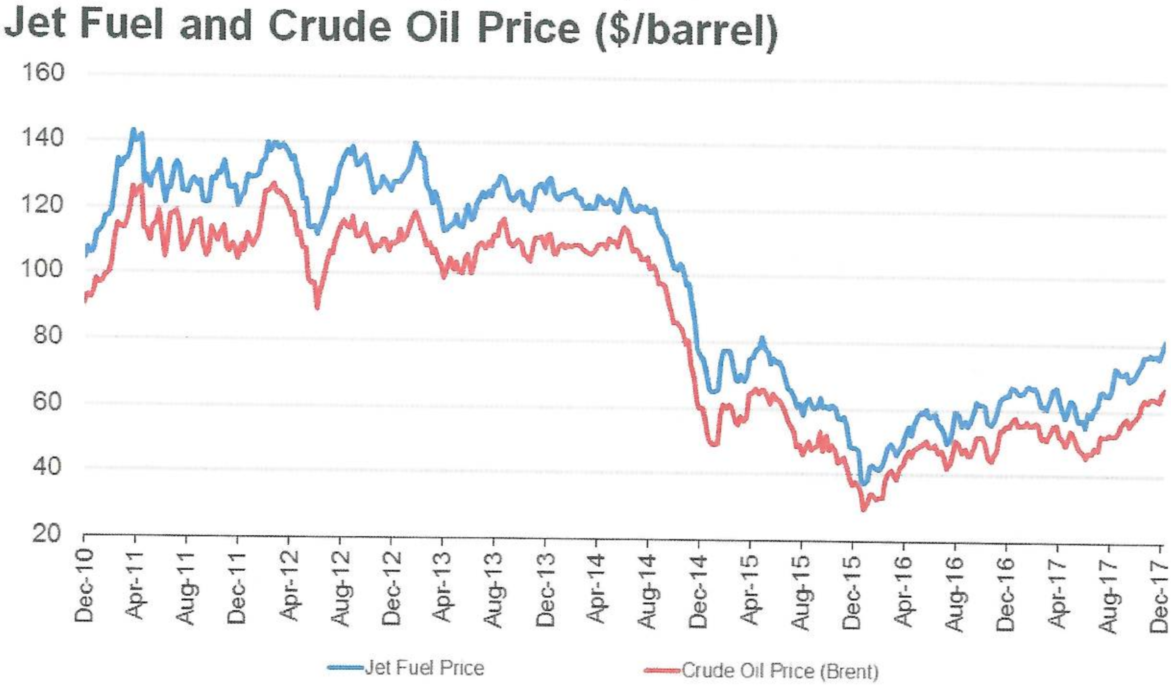
This research aims to analyze impacts, benefits and drawbacks of installing regenerative braking system on a typical regional jet as Embraer ERJ-190.

The regenerative system integrates with other aircraft systems, so it is not limited to the recovery of the landing kinetic energy but creates possibilities for the designer to reduce other components weight, size and drag and creates new scenarios for balancing conceptual decisions.

1.2 Motivation

Fuel price constantly oscillates and represents one of the higher costs of airlines. Figure 1 exhibits plots of Jet A-1 fuel along the last 7 years, published by IATA based on data by the energy industry information provider company Standard & Poor's Platts (INTERNATIONAL AIR TRANSPORTATION ASSOCIATION, 2017), followed by Figure 2 which shows United States airlines profit, according to IATA (PEARCE, 2017).

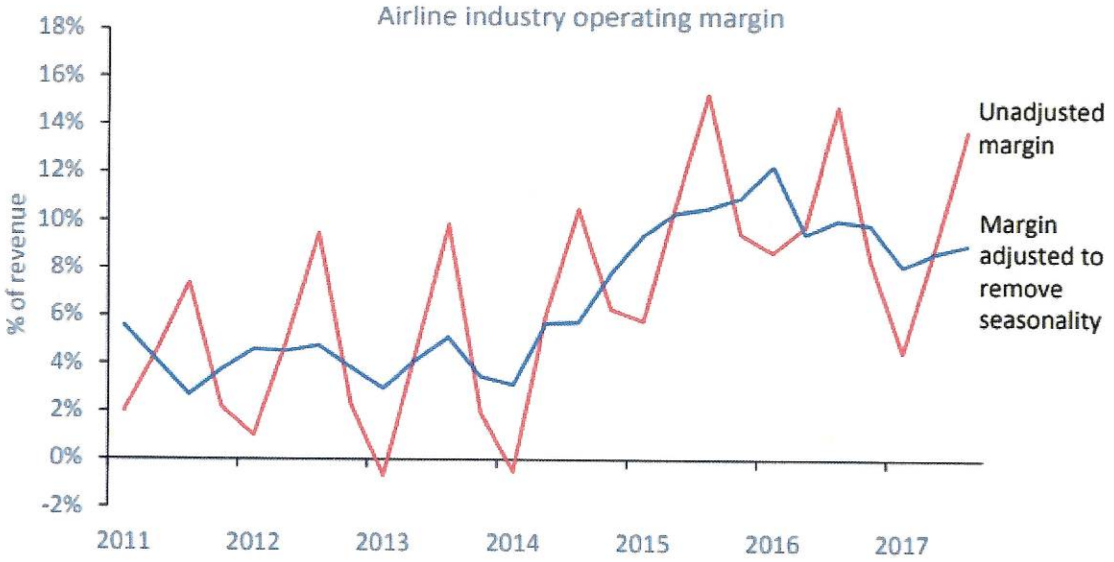
Figure 1 - Jet A1 price variation



Source: Platts, Oanda

Source: (INTERNATIONAL AIR TRANSPORTATION ASSOCIATION, 2017)

Figure 2 – Airlines revenue



Source: IATA Economics using data from The Airline Analyst and airline releases

Source: (PEARCE, 2017)

It is evident fuel price has a huge impact on airlines profit, but it is also evident airlines have found ways of profiting even on adverse fuel cost scenarios. For this reason, reducing fuel burn, noise and emissions are the main driver of future airplane developments. Airbus Fly Your Ideas (AIRBUS, [s.d.]), Europe's Flightpath 2050 (EU HIGH LEVEL GROUP ON AVIATION RESEARCH, 2011), Clean Sky (CLEAN SKY RESEARCH PROGRAMME, [s.d.]) and NASA Green X-Planes (BANKE, 2016) are practical examples of programs to motivate development of greener aircrafts and are mostly financed by companies and governments. In general, aircrafts developed under this program such as The MIT M8 concept aircraft (GREITZER et al., 2010a, 2010b) uses electricity to avoid bleeding pressure from engines to improve efficiency.

It is also notable there many initiatives in creating multifunctional systems and different uses for aircrafts. An example of such application is transporting equipment for general communication which is done, today, by satellites. These initiatives aim to reduce global cost and emissions.

Recently developed aircrafts such as Boeing 787, Airbus A350 and Bombardier C Series, tackle these variables by using new generation engines with increased bypass ratios and lower airframe weight by widely employing carbon fiber structures. Boeing advertises 10 to 20% higher fuel efficiency in the same routes.

In addition, insertion of new players as Pilatus, Mitsubishi, Sukhoi and Comac in the market creates competition and reduces profit margins. Incorporation of a system that permits operating in new routes due limited airports, lower emissions, fuel burn and noise is critical for companies to maintain competitiveness.

Regenerative brake system integrated with aircraft reduces the total amount of parts and systems and provides means for using the system in other flight phases. Its installation enables operation at higher weights on runway limited airports, fuel burn reduction by producing better takeoff schedules, creates engine-off, silent taxi in and taxi out, avoids use of ground vehicles for push backs, reduces the constant tire changes and reduces or even eliminates APU and RAT use.

1.3 Text structure

This dissertation is structured as follows.

Section 1 is this **Introduction**.

A brief history of regenerative brakes, aircraft brakes and lithium batteries are presented. The text discusses that regenerative braking systems for aviation was impractical and possibly inconceivable up to the date lithium batteries were made available.

Section 2 features the **Literature review**.

This section gathers all applicable publications studied by the author to determine the current state of the art for regenerative brake systems, design methodology and simulations. Reference is made to related publications including patents

Section 3 brings relevant **ERJ 190 technical data.**

Since Embraer ERJ-190 is used for studying the installation of regenerative brakes on a real aircraft, its technical data is presented. This data includes the most relevant areas and dimensions, weight, systems descriptions, and operational limitations related to takeoff and landing.

Section 4 introduces the **Method.**

This section briefly states the sequence of steps adopted to estimate the impact of regenerative brake system in a regional jet as the Embraer ERJ 190.

Section 5 discusses **Benefits and drawbacks.**

This section exhibits the many benefits of installing a regenerative system as well as the main drawbacks. The analyses include how performance is affected by the dependence of the many choices presented to the designer. The installation of this system deeply affects how these choices will be made and creates new possibilities for the designer.

Section 6 proposes **System requirements**.

System requirements include energy, power and torque demand of a typical regional jet required for performance evaluation and equipment dimensioning. In addition, aviation authorities' certification requirements are analyzed, and compliance evaluations are stated.

Section 7 presents the **Model**.

This section presents the model created to calculate takeoff performance. The modelling process is in accordance with AC 25-7C section 25.111 with all applicable restrictions and considers takeoff as a sum of several segmented speed or altitude targets. Modeling is matched to ERJ-190 flight test results and uses flight test data as the primary source of information for establishing coefficients.

Section 8 displays **Results.**

This section exhibits the results of simulations which consider the installation of regenerative brakes in their current state of the art and a simplified performance analyses for aircrafts sized up and down in respect to the ERJ-190. It is important to note that simulations data are calibrated by actual ERJ-190 flight test data.

Section 9 presents the **Conclusion**.

Conclusion section unites all other sections and ponders benefits and drawbacks of the regenerative braking system installation. It is evident the system weight penalty cannot be overcome by a single benefit as some similar systems do. However, integration with other systems and making use of it benefits the system is viable.

2 LITERATURE REVIEW

Literature review was performed to assure the state-of-the-art is being considered in both conceptual analysis and proposed solution. Several technical publication bases were used as well as respected authors' books and company owned documents. The most relevant are described below:

- IEEE – Institute of Electrical and Electronics Engineers
- AIAA – American Institute of Aeronautics and Astronautics
- NASA STI – National Aeronautics and Space Administration Scientific and Technical Information
- FAA – Federal Aviation Authority Regulations database
- EMBRAER SA Operators Manual database
- EMBRAER SA Technical publications database

2.1 Related work

Even though the integrated, full use of managing the kinetic energy in aircrafts is innovative, the regenerative braking idea has been studied by other researchers around the world.

A search for "electric brakes for aircrafts" results in a huge number of patents. Most of them, however, are modifications to the current hydraulic actuation systems of carbon brake disks and do not refer to electric energy generation from wheel torque. Three papers however, are similar to the proposed scope of this research and are further commented.

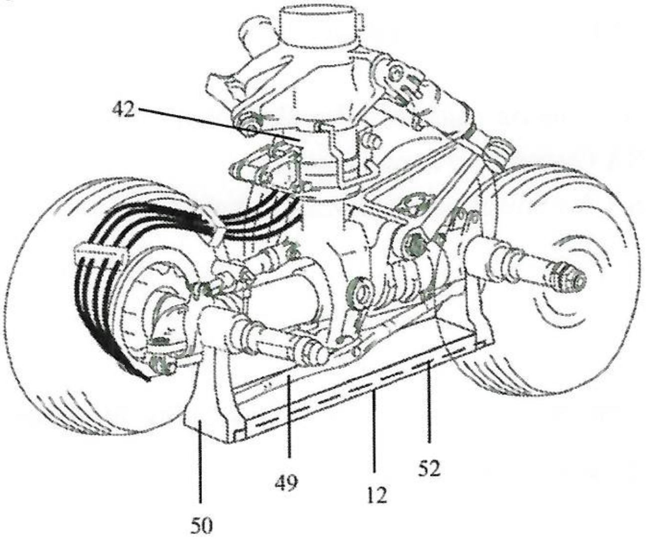
Shamus Zulkifli in his PhD thesis (ZULKIFLI, 2012), analyzed the possibility for harvesting braking energy, accumulate it and use it power the airport. Zulkifli, being an electrical engineer, approached the problem by analyzing the generators and the controllers but did not consider the feasibility of such system.

It is clear a regenerative braking system using current state-of-the-art components available in 2016 has a significant weight penalty which reduces aircraft performance or increases fuel burn. The additional fuel was not considered by Zulkifli and offsets by many times the amount of energy harvested by the system during landing.

For a matter of comparison Jet A-1, which is the most common aviation fuel, energy density is 42.8MJ/kg while best electric system energy densities are still below 1MJ/kg. For this reason, it seems senseless to harvest energy using a system on board of an aircraft to power outside systems when there are more economic alternatives.

Patent US8123163B2 (MCCOSKEY; VANDER WEL; JOHNSON, 2012) from 2008 register a regenerative braking system which harvests energy from landing and may receive additional energy during takeoff using a conductive shoe on the landing gear as illustrated in Figure 3.

Figure 3 – Patent US8123163B2 landing gear arrangement



Source: (MCCOSKEY; VANDER WEL; JOHNSON, 2012)

This system would require every airport to be modified at unconsidered cost and do not consider scenarios as bouncing, landing at other unprepared sites and reliability. Argumentation provided in the patent description makes no reference to actual aircraft performance, and can be considered superficial as it presents statements as follows:

> "...Current friction brake systems must also be capable of absorbing and dissipating the entirety of the kinetic energy from stopping a fully loaded aircraft upon an aborted takeoff as heat. This requirement demands that the current brake systems have enough mass to absorb stopping energy and forces the design of a system that is much heavier than actual operational service requirements needs. This is extremely inefficient and requires excess material mass that is parasitic weight to an aircraft's flight mission, further penalizing the aircraft in fuel efficiency, procurement costs and maintenance expenses." (MCCOSKEY; VANDER WEL; JOHNSON, 2012)

The cited authors did not consider that the mass of each carbon disks brakes is in order of 0,08% of the total aircraft mass and the fact that the proposed system also weights something. On the other hand, the idea of not having to carry along all flight a system that is only used on ground operations relates to the regenerative braking idea when a multipurpose system is created.

Dr. Martin Hepperle from the German Aviation Institute wrote a paper about electric flight potential and its limitations to register his analyses on electric powered aircraft (HEPPERLE, 2012). Dr. Hepperle concludes it is not reasonable to build such aircrafts with current technology for passenger transportation even after optimization on the current designs. The limitations scales with aircraft size.

Because Dr. Hepperle studies considers state-of-the-art electric power systems in 2009, his work contains valuable conceptual data for developing the regenerative braking system.

2.2 System requirements

System requirements are mostly based on current regional jets operation and certification aspects. For this reason, the following publications of aviation authorities such as Code of Federal rules 14 Part 25 (FAA) (FEDERAL AVIATION ADMINISTRATION, 1964) and the European Aviation Safety Agency regulation EASA CS 25 (EUROPEAN AVIATION SAFETY AGENCY, 2008) were used as reference mainly for guiding the determination of the required system.

Embraer ERJ-190 actual flight test data reports generated for certifying the carbon brake system were used and results are registered on report 190FTR014 - Maximum brake energy (EMBRAER, 2005a)

Decisions on systems weight and dimensions were based on circular documents as Federal Aviation Authority FAA AC 25-7C (FEDERAL AVIATION ADMINISTRATION, 2012) and FAA AC43-13 1B (FEDERAL AVIATION ADMINISTRATION, 1998).

Finally, taxi constraints were assessed using International Civil Aviation Organization (ICAO) Annex 16 Environmental Protection chapter for standard taxi procedures, noise and emissions analysis (INTERNATIONAL CIVIL AVIATION ORGANIZATION, 2015).

2.3 Current technology and future developments

Considering the regenerative brake system is composed of electric generator/motors, motor controllers and an energy storage device, publications for this section are related to these components as well as their applications on aviation or other high-performance vehicles.

FIA Formula 1 2009 Technical Regulations (FEDERATION INTERNATIONALE DE L'AUTOMOBILE, 2009) was used as baseline for KERS as it was the first introduction of this system and FIA Formula 1 2014 Regulations (FEDERATION INTERNATIONALE DE L'AUTOMOBILE, 2011) was considered for comparative weight and performance analyses as it establishes the highest values for generation and propelling using these systems at 120kW.

Motors/generators and drive trains were assessed mainly on recognized institutions papers. Tesla Motors, the American car manufacturer, and Siemens AG, a multinational company, have both developed and used the state-of-the-art motors available to public. While Tesla developed motors for cars peaking 400kW, Siemens developed an aircraft electric motor of 50kg outputting 260kW. Unfortunately, none of the above have their specifications fully documented so both cases are used as weight and size reference for the state-of-the-art motor publicly available.

Motor are generally size- and weight-limited to their heat transfer capacity. For this reason, Morega and colleagues' work on heat transfer analysis in the design phase of a high temperature superconductor motor (MOREGA et al., 2010) was studied, and provided insight and expectations for the possibility of a much lighter system to be designed in future.

New developments in this area involves toroidal drive train as presented by Carbone in his study on KERS technology (CARBONE et al., 2013). This article compares the use of double toroidal variator with other toroidal variators and concludes it is best to use the double toroidal variator. Since it is required to transmit power from wheels to motors on a given and ideally variable ratio the designer might use this solution. Since neither analysis for extreme power levels nor there is a mention of robustness and reliability of such system in this paper, care must be taken if this drive train is to be used.

Lithium batteries have also evolved greatly during the last ten years being Japan the leading country in this subject. For this reason, Masaki Yoshio and his co-authors' book on lithium-ion batteries (YOSHIO; BRODD; KOZAWA, 2009) were considered as well as the book edited by Yuping Wu on the same subject (WU, 2015) even though the last was considered superficial. Linden and Reddy's Handbook of Batteries (LINDEN; REDDY, 2002) was especially helpful for determining batteries properties specifications.

Christensen and colleagues' paper (CHRISTENSEN et al., 2012) was also studied for understanding future technologies.

2.4 Expected performance gains and drawbacks

Expected performance gains and drawbacks section describe conceptual gains into installing the proposed system considering current certification aspects. For this reason, regulations as CFR Part 25-14 (FEDERAL AVIATION ADMINISTRATION, 1964) and EASA CS 25 (EUROPEAN AVIATION SAFETY AGENCY, 2008) were extensively used together with FAA AC 25-7C (FEDERAL AVIATION ADMINISTRATION, 2012).

Since the conceptual analyses require considerable knowledge of flight mechanics and aerodynamics, works by Danie P. Raymer and Ralph Kimberlin were extensively used. (RAYMER, 1992) (KIMBERLIN, 2003).

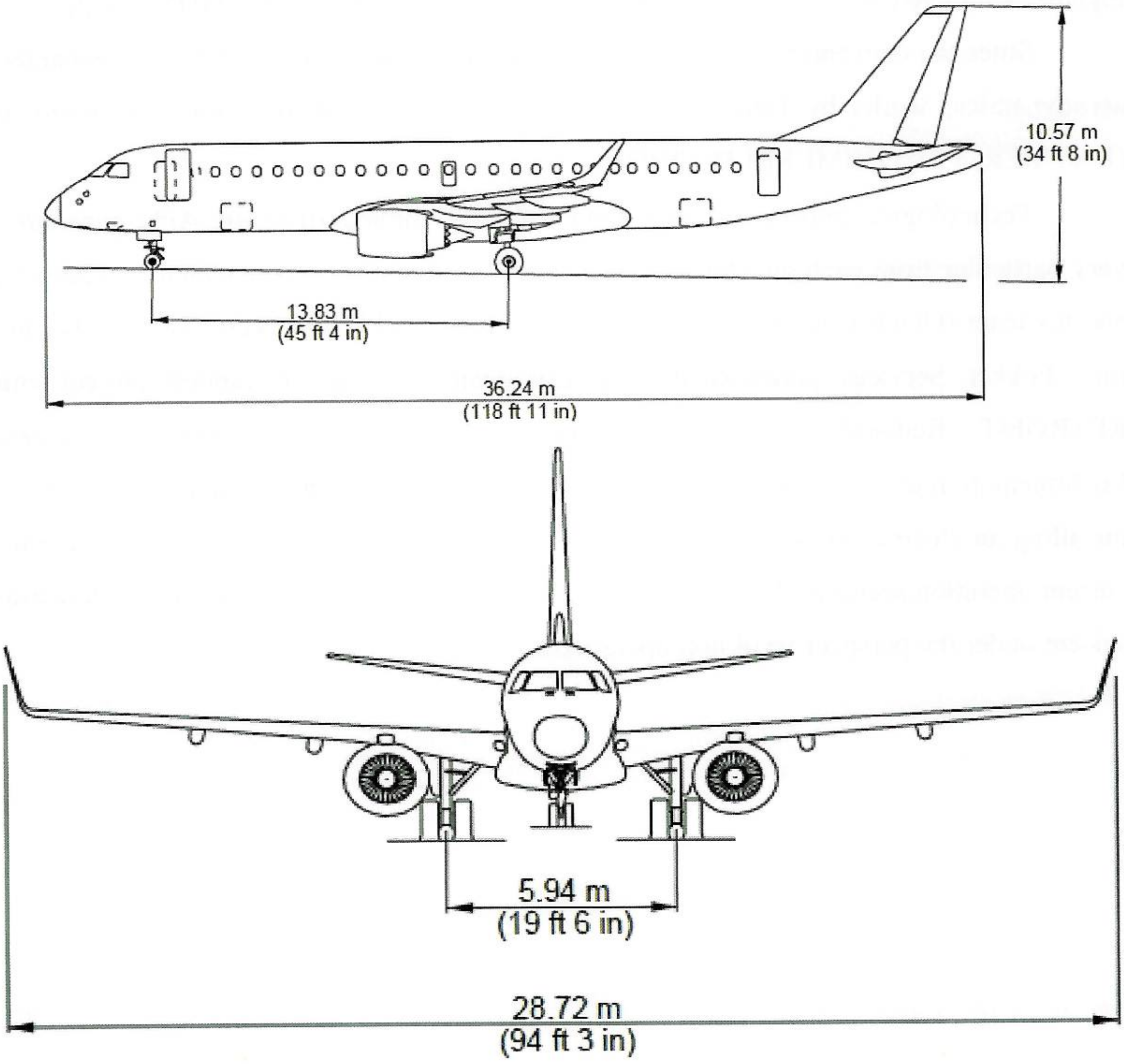
Technological aspects of the system were also subject of study. APU generators are very particular from each aircraft; however, its noise signature was assessed by Gugliermetti and his team (GUGLIERMETTI et al., 2010). Electric taxi is also seen a benefit, because of this, Fokker Services participated in a European Commission funded project entitled RETROFIT Reduced Emissions of Transport Aircraft operations by Fleetwide Implementation of New Technology (CHILTON et al., 2012) which discusses the benefits of installing an electric taxi system on Boeing 737 and Airbus A320 and A330 considering the current operation scenario. This study is base for viability analyses of the regenerative braking system under the perspective of taxi operations.

3 EMBRAER ERJ-190 TECHNICAL OVERVIEW

This section presents general ERJ-190 technical data that can be used to estimate performance and requirements for the proposed system. Embraer ERJ-190 is commercial, regional, jet aircraft manufactured by Embraer SA and certified in 2005 by Agência Nacional de Aviação Civil (ANAC) as in Type Certificate Datasheet 2005T13 (AGÊNCIA NACIONAL DE AVIAÇÃO CIVIL, 2012).

Figure 4 can be referenced for general dimensions.

Figure 4 - Embraer ERJ-190 general dimensions



Source: (EMBRAER, 2008a)

All technical data presented in this section was extracted from Embraer manuals, available to customers as the Airplane Maintenance Manual - AMM (EMBRAER, 2008a) and the Airplane Flight Manual – AFM (EMBRAER, 2005b). These data however, must be corrected for each airframe as areas and aerodynamics are singular and may distort results if not properly calculated.

According to Raymer's motion equations presented in his book (RAYMER, 1992), the minimum parameters to be determined for evaluating ground performance are engine performance, mass properties, areas and arms, aerodynamic coefficients (mainly drag and lift for a given flap/slat and spoiler configuration) and systems characteristics.

Lift augmentation devices as flaps and slats as well as lift reducers and drag generators as spoilers are extremely important for analyses. Since the regenerative braking system must be able to operate along all flight and mass envelope, the extremes are generally selected as initial conditions and their results expanded.

Less deflected flaps tend to produce higher stall speeds and lower drag coefficient so most of the critical takeoff performance analyses is conducted for flap 1. The same is applicable to landing but since limited performance operations are conducted at lower speed normally flap 6 is chosen for conducing landing analyses.

Embraer ERJ-190 flap and slat positions are commanded by the pilot via a flap lever which has discrete positions from 0 to FULL as presented in Table 1.

Table 1 - Lever, flap and slat positions

Flap setting position	Inboard flap (main / aft)	Outboard flap	Slat position	
			1	2, 3 & 4
0	0.0° / 0.0°	0°	0.0°	0.0°
1	7.1° / 15.4°	7.0°	12.0°	15.0°
2	10.1° / 16.6°	10.1°	12.0°	15.0°
3	20.2° / 19.2°	20.0°	12.0°	15.0°
4	20.2° / 19.2°	20.0°	20.0°	25.0°
5	20.2° / 19.2°	20.0°	20.0°	25.0°
Full	37.1° / 22.0°	36.5°	20.0°	25.0°

Source:(AGÊNCIA NACIONAL DE AVIAÇÃO CIVIL, 2012)

Powered by two CFM-34 engines manufactured by General Electric, Embraer ERJ-190 has three engine part number possibilities. It is crucial for any designer to precisely know engine thrust at every rating and speed to perform takeoff or landing analyses. Variations and corrections of engine thrust can be found in the paper written by Hughes (HUGHES, 1981). Despite these corrections, precise engine performance data is measured along test flight campaign; even though data is not presented in this document, it was considered for simulations.

Table 2 shows the maximum static thrust for CF34-10E7 to be used as reference. Data presented considers sea level altitude and standard conditions.

Table 2 - Engine thrust schedules

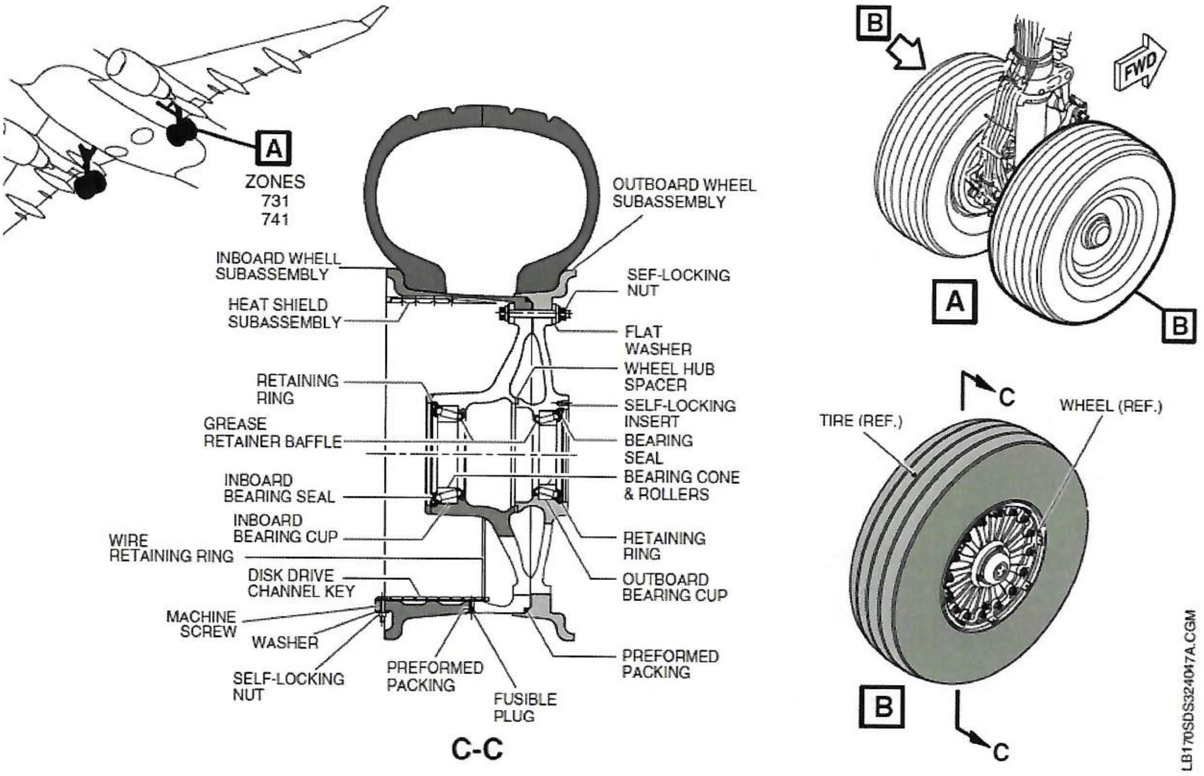
		CF34-10E7		CF34-10E5A1		CF34-10E5		CF34-10E2A1	
Ratings		Thrust (lbf)		Thrust (lbf)		Thrust (lbf)		Thrust (lbf)	
Thrust Mode	ATTCS	All Engine Oper.	One Engine Inop.	All Engine Oper.	One Engine Inop.	All Engine Oper.	One Engine Inop.	All Engine Oper.	One Engine Inop.
T/O-1	ON	18500	20000	–	–	17100	18500	–	–
	OFF	18500	18500	18500	18500	17100	17100	16650	16650
T/O-2	ON	17100	18500	17100	18500	15450	16650	15450	16650
	OFF	17100	17100	17100	17100	15450	15450	15450	15450
T/O-3	ON	15450	16650	15450	16650	–	–	–	–
	OFF	15450	15450	15450	15450	–	–	–	–
GA	ON	18500	20000	17100	18500	17100	18500	16650	16650
CON	–	16255	16255	16255	16255	16255	16255	14310	14310
CLB-1	–	15950	–	15950	–	15950	–	14020	–
CLB-2	–	14020	–	14020	–	14020	–	–	–
CRZ	–	13830	–	13830	–	13830	–	12080	–

Source: (EMBRAER, 2012)

3.1 Wheel assembly

ERJ-190 is equipped with four main wheels, two at each main landing gear, and two nose landing gear wheels. Main landing gear wheels are composed of two subassemblies surrounded by a rubber tire and is mounted into landing gear main structure be means or two conic rollers and a retaining nut. These wheels are equipped with carbon disk brakes, mounted inside them as depicted in Figure 5.

Figure 5 - ERJ-190 wheel assembly

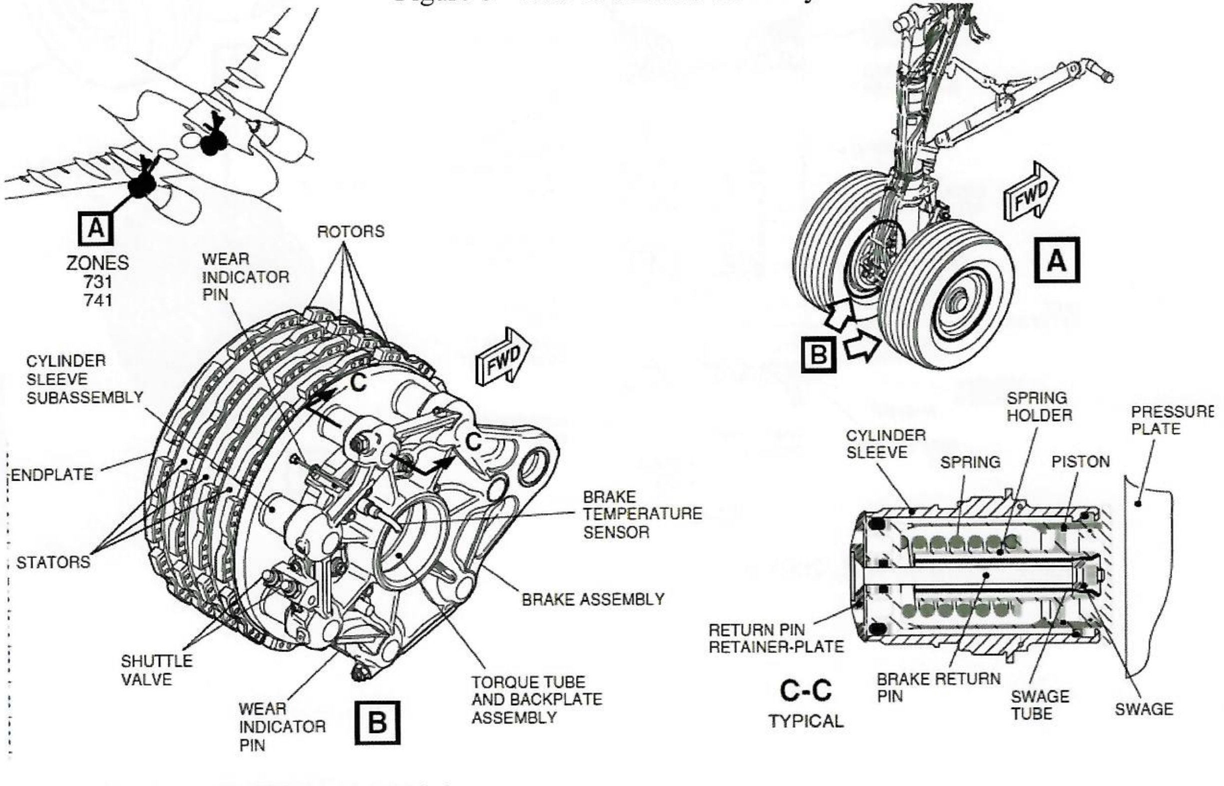


Source: (EMBRAER, 2008a)

3.2 Brakes

Brakes are depicted in Figure 6. Each brake consists of an aluminum housing that conceals spring loaded pistons and hydraulic lines, a steel torque tube in which stator and rotor carbon disks are alternatively mounted. Rotor disks transfer torque to the wheels via the drive channel keys so in case hydraulic pressure is applied, pistons are extended and press stator disks into the rotor disks, limited by the torque tube end plate. In this configuration, the compression of the disks generates friction, hence torque and braking action is started. When pressure is relieved, piston springs return pistons to their original position. Frictioned carbon disks are heated during the process accumulating braking energy. This energy is transferred to the surrounding air and other landing gear components as the wheels via irradiation and conduction.

Figure 6 – ERJ-190 Brake assembly

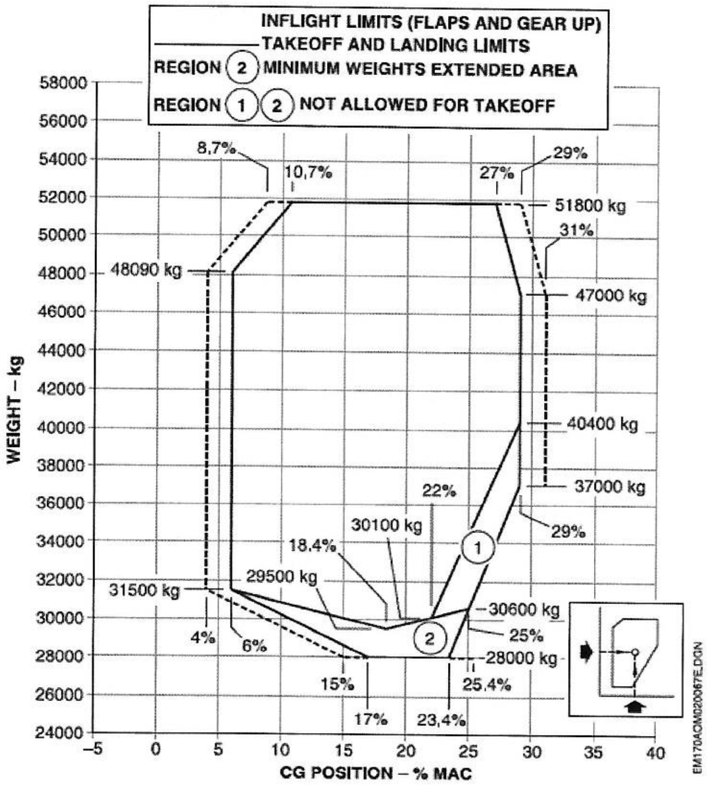


Source: (EMBRAER, 2008a)

3.3 Flight envelope

Considering most of the landing and rejected takeoff tests and analyses are performed at the most unfavorable condition of CG and weight as in FAA FAR 25.733 and 25.735 (FEDERAL AVIATION ADMINISTRATION, 1964), ERJ-190 weight and CG chart is displayed in Figure 7 as presented to flight crew in the AFM (EMBRAER, 2005b).

Figure 7 - ERJ-190 Weight and CG envelope



Source: (EMBRAER, 2005b)

.4 METHOD

Current contributions to regenerative braking are not particularly aimed at takeoff performance or system integration but rather on energy efficiency. Landing kinetic energy is minimal part the global energy involved during a flight, nearly as large as the takeoff run energy. Roughly Embraer ERJ-190 fuel flow during takeoff is 2500kg/hour/engine but since the take run lasts for 30s the amount of energy is equivalent to the useful energy of 40kg of fuel, note a 750Nm typical flight consumes 3600kg of fuel.

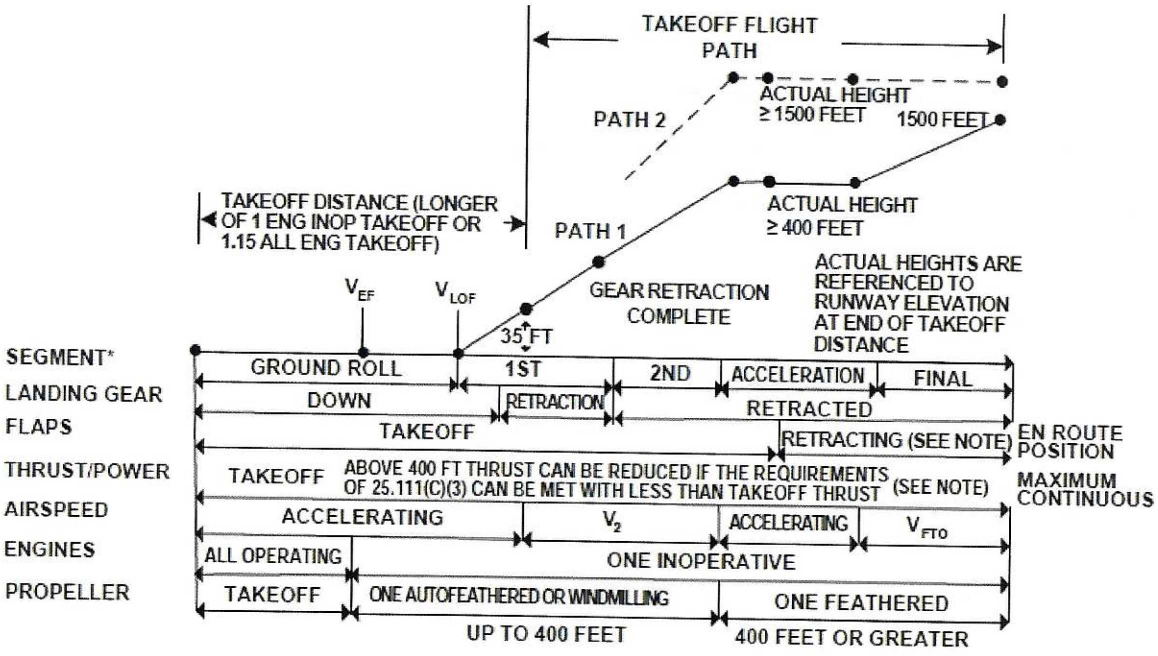
For this reason, the installation of regenerative brakes on a regional jet should not aim on efficiency of the landing process but rather on providing energy to the aircraft at very specific moments when extra power is important.

Some systems in the aircraft are not designed to work continuously but are installed to be used during a failure scenario as backup batteries and the Ram Air Turbine. Other systems as Auxiliary Power Unit are designed to facilitate ground operations and may be used as a backup generator during flight. Bleed air from the engines to provide environmental system pneumatic energy is also mandatory on current designs. Unlike other systems, bleeding air from the engines has a direct impact on fuel consumption as the whole Brayton cycle suffers efficiency loss as pressure is reduced. On all cases, the installation of these systems is mandatory but come at a weight penalty which has no benefit for flight performance. The first part of this document exhibits the assess on how the integration of a regenerative brake system is able to reduce parts count and possibly weight of whole aircraft.

The second part of this document exhibits the assess of how regenerative brakes can affect actual performance during flight. Takeoff and taxi are two specific flight phases that can benefit from this system. Autonomous pushbacks a silent, engine saving, emission free taxis are convenient not only for fuel savings but also reducing cycle time and impact to the surroundings. Takeoff however, determines load capacity and general performance as compromises at the rudder, landing gear, engines sizing and wing area have to be made in order to operate under certain conditions. Adding energy to the takeoff run changes how these compromises are made and creates a new path for designing aircraft.

Takeoff modeling permits the precise evaluation of the impact the installation of a regenerative brake system has on the aircraft. By comparing the certified ERJ-190 aircraft performance to the assisted takeoff performance one can conclude on how much and when the system is usable. In order to assess takeoff performance AC25-7C section 25.111 segmented runway method was used as in Figure 8.

Figure 8 - Segmented takeoff path



Source: (FEDERAL AVIATION ADMINISTRATION, 2012)

The author of this dissertation used Microsoft Visual Basic to implement the model that integrates net propelling or braking force which produces acceleration along time to determine speed and position, according to AC 25-7C (FEDERAL AVIATION ADMINISTRATION, 2012).

Additionally, the normal loads on the wheels are calculated during takeoff run. The available torque, considering a reasonable value of mi brake coefficient, at each wheel is used to determine the maximum propelling force during takeoff run which may or may not be used during calculations to compare the assisted to the regular takeoff path.

Finally, results of the modeling and a conclusion is presented to the viability of installing a regenerative braking system at the Embraer ERJ-190.

5 BENEFITS AND DRAWBACKS

This section discusses the benefits and drawbacks of installing a regenerative brake system in a regional jet. Considering aircrafts are complex and it systems are highly integrated, benefits are either on replacing parts, reducing parts count or creating operational advantages in cycle time, fuel consumption or expanding the performance envelope.

5.1 Additional energy for takeoff

The ability to add energy to the takeoff run is most important reason for installing a regenerative braking system. As per system requirements, the generators and accumulation system must be able to at least harvest as much power and as much energy as the brake disks it is reasonable to assume a similar amount can be output back to the wheels while taking off.

Outputting the same amount of energy would accelerate the aircraft as if an additional engine was present. Additional power can be converted to either more load in the same runway length or shorter takeoff runs in the same weight.

On the other hand, since acceleration capacity relies on the capacity of outputting power through the wheels, and keeping in mind the fact that the aircraft must be able to accelerate to rotate speed V_R in the remaining runway, decision speed V_1 must be variable with this capacity by either remaining energy stored or system temperature. V_1 as defined by FAA FAR 25.107 as:

> "...(a) V_1 must be established in relation to V_{EF} as follows:
>
> (1) V_{EF} is the calibrated airspeed at which the critical engine is assumed to fail. V_{EF} must be selected by the applicant, but may not be less than V_{MCG} determined under §25.149.
>
> (2) V_1, in terms of calibrated airspeed, is selected by the applicant; however, V_1 may not be less than V_{EF} plus the speed gained with critical engine inoperative during the time interval between the instant at which the critical engine is failed, and the instant at which the pilot recognizes and reacts to the engine failure, as indicated by the pilot's initiation of the first action (e.g., applying brakes, reducing thrust, deploying speed brakes) to stop the airplane during accelerate-stop tests."

In case a reject takeoff (RTO) procedure, there must be enough brake capacity to stop the airplane before the end of the runway after 2s delay for failure recognition as determined in FAA FAR 25.109. Limited runway lengths drive most of the design of an aircraft. A balance between weight, flaps deflection, wing area and fuel consumption as based on a typical mission profile. The shorter the runway, the more wing area is required leading to addition stabilizers area, weight and of course higher fuel consumption during cruise and climb. The addition ability to takeoff on limited runways allows the designer to optimize wings for cruise performance while maintaining the capacity to takeoff.

In order to improve takeoff performance on short runways, a climb compromise is made by using wing area and flaps deflection. Climb gradient can be simplified by the difference between thrust and drag divided by weight. The more flaps are deflected, the larger is drag, the lower can be rotation speed V_R and V_2. However, this ability is limited by the capacity to takeoff with a single engine. FAA FAR 25.121 defines minimum climb gradient in this condition for three flight phases, takeoff with landing gear extended, takeoff after landing gear retraction and final takeoff:

> "...(a) Takeoff; landing gear extended. In the critical takeoff configuration existing along the flight path (between the points at which the airplane reaches V_{LOF} and at which the landing gear is fully retracted) and in the configuration used in §25.111 but without ground effect, the steady gradient of climb must be positive for two-engine airplanes, and not less than 0.3 percent for three-engine airplanes or 0.5 percent for four-engine airplanes, at V_{LOF} and with—
>
> > (1) The critical engine inoperative and the remaining engines at the power or thrust available when retraction of the landing gear is begun in accordance with §25.111 unless there is a more critical power operating condition existing later along the flight path but before the point at which the landing gear is fully retracted; and
> >
> > (2) The weight equal to the weight existing when retraction of the landing gear is begun, determined under §25.111.
>
> (b) Takeoff; landing gear retracted. In the takeoff configuration existing at the point of the flight path at which the landing gear is fully retracted, and in the configuration used in §25.111 but without ground effect:
>
> > (1) The steady gradient of climb may not be less than 2.4 percent for two-engine airplanes, 2.7 percent for three-engine airplanes, and 3.0 percent for four-engine airplanes, at V_2 with:
> >
> > > (i) The critical engine inoperative, the remaining engines at the takeoff power or thrust available at the time the landing gear is fully retracted, determined under §25.111, unless there is a more critical power operating condition existing later

along the flight path but before the point where the airplane reaches a height of 400 feet above the takeoff surface; and

(ii) The weight equal to the weight existing when the airplane's landing gear is fully retracted, determined under §25.111.

(2) The requirements of paragraph (b)(1) of this section must be met:

(i) In non-icing conditions; and

(ii) In icing conditions with the most critical of the takeoff ice accretion(s) defined in Appendices C and O of this part, as applicable, in accordance with §25.21(g), if in the configuration used to show compliance with §25.121(b) with this takeoff ice accretion:

(A) The stall speed at maximum takeoff weight exceeds that in non-icing conditions by more than the greater of 3 knots CAS or 3 percent of V_{SR}; or

(B) The degradation of the gradient of climb determined in accordance with §25.121(b) is greater than one-half of the applicable actual-to-net takeoff flight path gradient reduction defined in §25.115(b).

(c) Final takeoff. In the en route configuration at the end of the takeoff path determined in accordance with §25.111:

(1) The steady gradient of climb may not be less than 1.2 percent for two-engine airplanes, 1.5 percent for three-engine airplanes, and 1.7 percent for four-engine airplanes, at V_{FTO} with—

(i) The critical engine inoperative and the remaining engines at the available maximum continuous power or thrust; and

(ii) The weight equal to the weight existing at the end of the takeoff path, determined under §25.111.

(2) The requirements of paragraph (c)(1) of this section must be met:

(i) In non-icing conditions; and

(ii) In icing conditions with the most critical of the final takeoff ice accretion(s) defined in Appendices C and O of this part, as applicable, in accordance with §25.21(g), if in the configuration used to show compliance with §25.121(b) with the takeoff ice accretion used to show compliance with §25.111(c)(5)(i):

> (A) The stall speed at maximum takeoff weight exceeds that in non-icing conditions by more than the greater of 3 knots CAS or 3 percent of V_{SR}; or
>
> (B) The degradation of the gradient of climb determined in accordance with §25.121(b) is greater than one-half of the applicable actual-to-net takeoff flight path gradient reduction defined in §25.115(b)…"

It is important to notice that it is acceptable to have marginal climb gradients while landing gear is extended as drag contribution of this system is enormous. Then when landing gears are retracted the minimum climb gradient is greatly increased to more than 2% and after en route configuration is established and thrust reduced to maximum continuous regime climb is accepted to be lower.

Regenerative brake system installation can accelerate more mass to higher speeds in the same runway. This creates new possibilities to designer by changing wing area to flap compromise and improving takeoff weight while still maintaining single engine climb gradient.

On the other hand, wing area modifications implies in stall speeds modifications. For this reason, it is important to note landing capacity not only relies on braking performance but also on reference speed, V_{REF}. FAA FAR 25.125 defines V_{REF} as:

> "… (2) A stabilized approach, with a calibrated airspeed of not less than V_{REF}, must be maintained down to the 50-foot height.
>
> (i) In non-icing conditions, V_{REF} may not be less than:
>
> (A) 1.23 V_{SR0};"

Since V_{REF} is related to stall speed, smaller wings lead to higher V_{REF}s hence longer runway lengths for deceleration. In order to maintain V_{REF}, maximum landing weight (MLW) however can be defined by the designer as lower without much performance loss for the operator.

Long runways would not require the use of this system, however since aircrafts basic parameter are defined by short runway operation ability, one can conclude from this discussion that the ability to output power during takeoff run dramatically changes aircraft configuration by permitting change on wing area and flap deflection improving cruise and takeoff performance.

5.2 V_{MCG} reduction

Minimum control on ground speed (V_{MCG}) is defined by FAA FAR25.149 as:

> "...(e) V_{MCG}, the minimum control speed on the ground, is the calibrated airspeed during the takeoff run at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane using the rudder control alone (without the use of nosewheel steering), as limited by 150 pounds of force, and the lateral control to the extent of keeping the wings level to enable the takeoff to be safely continued using normal piloting skill. In the determination of V_{MCG}, assuming that the path of the airplane accelerating with all engines operating is along the centerline of the runway, its path from the point at which the critical engine is made inoperative to the point at which recovery to a direction parallel to the centerline is completed may not deviate more than 30 feet laterally from the centerline at any point. V_{MCG} must be established with—
>
> (1) The airplane in each takeoff configuration or, at the option of the applicant, in the most critical takeoff configuration;
>
> (2) Maximum available takeoff power or thrust on the operating engines;
>
> (3) The most unfavorable center of gravity;
>
> (4) The airplane trimmed for takeoff; and
>
> (5) The most unfavorable weight in the range of takeoff weights...."

V_{MCG} situation implies in rudder deflected to its maximum position (excluding tolerances) at the most unfavorable CG and weight. As predecessor section states, V_1 balances runway performance by either granting there is enough runway to perform an RTO or accelerate to V_R before its end. Ideally V_1 would be defined as 0kt so all runway length would remain for acceleration to rotate speed V_R.

However, FAA FAR 25.107 states:

> "...(a) V_1 must be established in relation to V_{EF} as follows:
>
> (1) V_{EF} is the calibrated airspeed at which the critical engine is assumed to fail. V_{EF} must be selected by the applicant, but may not be less than V_{MCG} determined under §25.149(e)..."

Since decision speed V_1 cannot be lower than V_{MCG} the designer normally compromises rudder area and deflection and thrust to be able maintain V_1 as low as reasonable. Additional rudder area adds weight and drag during cruise phase. Typically, on commercial airplanes, vertical stabilizer summed to an undeflected rudder represents 8% of total drag during cruise.

In case of one engine failure, and considering it is possible to create a momentum using regenerative braking system by accelerating the critical side wheel and reduce acceleration on the other side wheel V_{MCG} can be lowered or even reduced to zero, mainly on fuselage mounted engines.

V_{MCG} reduction leads to V_1 drastic reduction which, in addition to improved acceleration, permits the designer to reduce vertical stabilizer area, weight and optimize takeoff and cruise capacity on an unpreceded manner.

5.3 Ram Air Turbine replacement

The Ram Air Turbine (RAT) is a relative wind driven electric generator mounted in the aircraft to provide electric energy in case of the engine and APU generators are not available. This combination might happen on various scenarios as a dual engine failure due to lack of fuel.

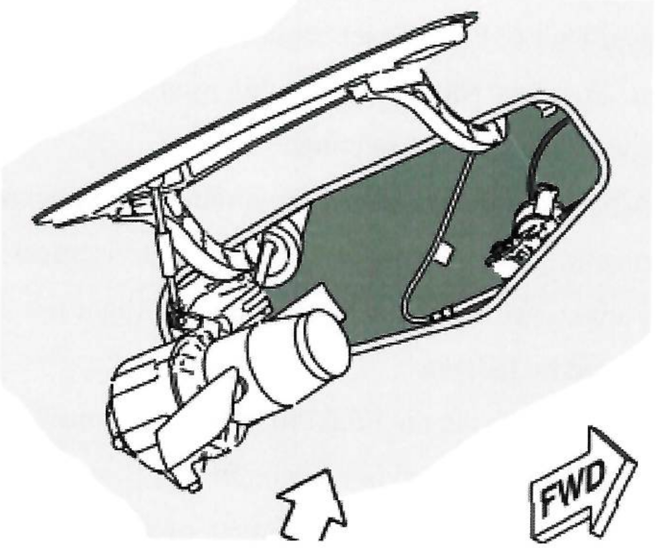
Most flight controls systems are hydraulic and required hydraulic power to operate. RAT energy is used, among other systems, to provide energy to Hydraulic 3 system which powers some flight control surfaces for the emergency landing. Additionally, RAT provides energy for essential lights, communication equipment, avionics and landing gear. ERJ-190 Aircraft Maintenance Manual describes the RAT as:

> "…The RAT is rated at 15 kVA, 115/200 VAC, 400 Hz at the POR (Point of Regulation).
>
> The turbine assembly of the RAT consists of two turbine blades connected to a mechanical governor, installed in a hub housing assembly. The outside diameter of the turbine blades is 24 in (609.6 mm).
>
> The mechanical governor maintains the rotating speed of the turbine within 7200 to 8800 rpm, depending on the aircraft airspeed, altitude and electrical load. The turbine hub assembly is connected to the generator shaft.
>
> The generator is a three-phase, air-cooled, AC machine. A small PMG (Permanent Magnet Generator) is mounted on the main generator shaft. The PMG provides power to the RAT GCU, which, in turn, provides the power to excite the main generator stator field…"

The installation of the RAT is in a non-pressurized, non-temperature controlled forward fuselage area as shown in Figure 9.

Considering the scenario, the RAT is deployed and considering the condition which prevents the use of other electric generators persists it is possible to replace the RAT and all its adjacent equipment by the regenerative braking system battery.

Figure 9 – Deployed RAT



Source:(EMBRAER, 2008a)

5.4 Reduced tire wear

Michelin tire care manual (MICHELIN, 2011) states tires must be changed every time the first ply is exposed. In average, Embraer EMB190, operating at Brazilian runways using tire part number M18602 wears tires after 570 cycles.

The associated maintenance services of changing tires are explicit at ABSC component maintenance manual for the wheel. Every tire change requires the operator to disassemble, clean, perform visual and eddy current inspections and reassemble with a new tire. At every 5 tire changes the operator must perform an overhaul which compromise the same maintenance steps of regular changes added by paint removal, die penetrant inspection, bolts and nuts inspection and repainting.

Considering wheels removed for maintenance services must be replaced by extra wheel assemblies, expenses tire and tire change associated costs, it is possible to estimate the cost of each landing for these components.

Regenerative braking system allows the pilot to spin up the wheels before touchdown reducing tire consumption. Large, heavy tires wear 20% on touch down by the spin up effect.

Additionally, used tires must be discarded by the operator at its expense in order to reduce environmental impact. Cost reduction is even higher than proportional cost since maintenance control, quality assurance, service providers' failures and delays and logistics costs are not included.

5.5 Auxiliary Power Unit

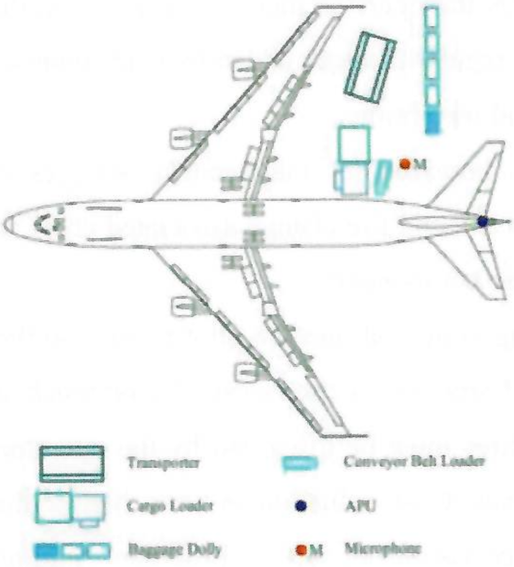
Auxiliary Power Unit (APU) is a jet engine, which consumes fuel from the fuel tank, normally mounted at aftermost part of the aircraft used to provide electric, hydraulic and pneumatic power while engines are not running.

In general, APU provides power for environmental systems (air conditioning and pressurization), pneumatic power for engines starting and electrical power for systems and lights. Once engines are started APU can be shutdown. Inflight use of the APU is permitted and is generally motivated by failures.

Peak APU power installed in the ERJ-190 is 40kVA. Considering regenerative braking system requires a battery bank installed in the aircraft it is possible to use its energy to power the same devices APU does for a limited amount of time depending on charge and if acceleration will be required during takeoff.

One of the most considerable noise sources on ground operations is the APU. Its high pitch and obvious presence during ground operations lead to airport workers' health issues and annoyance to passengers. APU and other noise sources and their impacts are studied by Gugliermetti (GUGLIERMETTI et al., 2010). This study measured the noise in various positions divided in groups of airport operators. Groups are located around the aircraft as depicted in Figure 10.

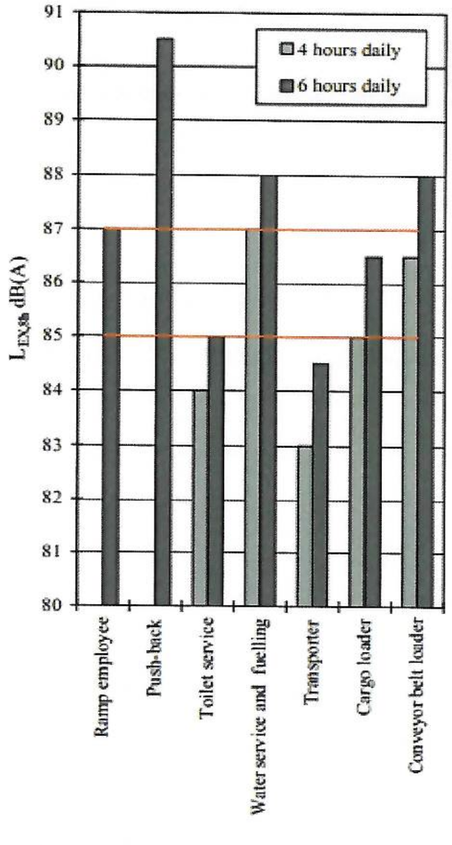
Figure 10 Noise measurement arrangement



Source: (GUGLIERMETTI et al., 2010)

The study concludes that not only specific measurements must be made but the whole airport operation must be analyzed as multiple aircraft ramp activities and ground support equipment in use. As a result, it is identified ramp, push-back, water service, cargo loader and belt loaders are exposed daily to higher than regulated noise levels leading these operators to require even more sophisticated protections, as Figure 11 shows.

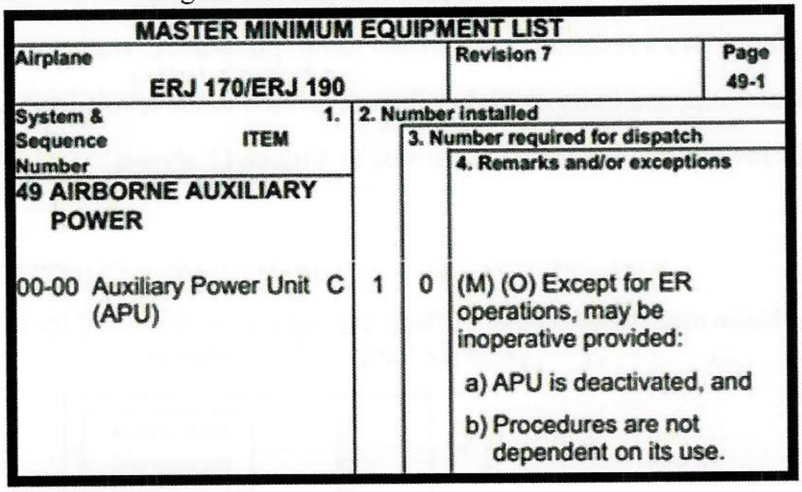
Figure 11 - Noise measurement results - daily exposure level calculated for each operator compared with the limits of the regulation



Source: (GUGLIERMETTI et al., 2010)

Just as any other system, APU is subject to failure. Dispatching a failed system is possible via Minimum Equipment List (MEL). Embraer EMB-190 Master Minimum Equipment List (MMEL) (EMBRAER, 2004) states the aircraft can be dispatched with an APU failure, after maintenance intervention, for no more than 5 days provided its use is not required, extended range flight operations will not be conducted, and other systems are monitored.

Figure 12 - ERJ-190 Master MEL



MASTER MINIMUM EQUIPMENT LIST

Airplane	Revision 7	Page
ERJ 170/ERJ 190		49-1

System & Sequence Number	ITEM	1.	2. Number installed	3. Number required for dispatch	4. Remarks and/or exceptions
49 AIRBORNE AUXILIARY POWER					
00-00	Auxiliary Power Unit (APU)	C	1	0	(M) (O) Except for ER operations, may be inoperative provided: a) APU is deactivated, and b) Procedures are not dependent on its use.

Source: (EMBRAER, 2004)

Reduction or removal of APU system reduces aircraft`s cost, weight, complexity, noise and emissions. In addition, the removal of whole system reduces the dispatching failure rate of any aircraft.

5.6 Electric taxi

Electric taxi is a tendency on aviation and has been developed be numerous companies. Some advantages of taxing using electric motors can be highlighted:

- Reduced fuel burn;
- Reduced emissions;
- Reduced noise;
- Autonomous pushbacks.

Fokker company created a business plan (JESSE; VAN AART; KOS, 2012) for retrofitting Airbus A320 and Boeing 737 with an electric motor powered by the APU to taxi. Incorrectly, Fokker assumed the weight of the system equals the fuel weight it saves during taxi. Even though true, the fuel consumed during taxi is not used during flight, so the system weight is not offset as it increases fuel burn along all flight phases.

This study demonstrates, using ICAO standard taxi cycle, calibrated by 2015 actual taxi data that there is reduction in emissions and fuel burn. Considering an average number of cycles for these aircrafts, Fokker quantified CO_2 emissions and fuel costs but did not considered cost savings of regular delays during ground operations. The result is displayed in Table 3.

Table 3 - Electric taxi cost savings per year

Aircraft	**Cost savings Euro/trip**		**Trips/year**	**Total/year (Thousand Eur)**
	Fuel	**Emissions**		
B737 series	247	12	1249	0,323491
A 320 series	215	10	1301	0,292725
A 330 series	631	30	904	0,597544

Source: (JESSE; VAN AART; KOS, 2012)

Embraer ERJ-190 has similar emission numbers but would average 182kg fuel saving for taxi on operations for 1853 cycles per year leading to very similar numbers as Boeing 737.

The study concludes 1 Million Euro as payback (hence 3 years) is reasonable for producing an electric taxi system. Regenerative braking system can perform the same way as the electronic taxi but may further reduce emissions and noise as the APU can be maintained shutdown or eliminated.

5.7 NiCd batteries removal

A pair of NiCd batteries are installed in Embraer ERJ-190 and are used as backup in case of engine driven electric generators failure or engine failures. These batteries are used to start the APU system power as well as powering the essential systems as flight controls in order to provide enough energy for at least twenty minutes after electric generation failure. FAA FAR25.1351 states the following:

> "...(d) Operation without normal electrical power. It must be shown by analysis, tests, or both, that the airplane can be operated safely in VFR conditions, for a period of not less than five minutes, with the normal electrical power (electrical power sources excluding the battery) inoperative, with critical type fuel (from the standpoint of flameout and restart capability), and with the airplane initially at the maximum certificated altitude."

In order to comply with the 5-minute requirements these batteries are made of 19 to 20 individual cells at 35Ah capacity and weights 24.6kg. In case of electric generation, failure systems are degraded and so is performance.

Since an installation of a battery bank is required for the regenerative braking system, NiCd batteries can be removed and weight saved. In addition, since the battery bank capacity is much higher, it is possible not to degrade systems and provide flight crew a less adverse situation in this critical condition.

5.8 Reduced landing gear loads

During touchdown the main landing gear is subject to two main stresses. One is normal to the landing gear and is directly related to the normal force being a consequence of vertical speed and acceleration. The other is orthogonal with the landing gear and is a consequence of wheel being accelerated to ground speed, commonly called spin-up. The first load is reacted mainly by the landing gear damper viscosity while the second is reacted by spring effect, commonly called spring-back. Once the wheel accelerated the landing gear will return to its original position. FAA FAR 25.473 (c) (2) states:

> "...(c) The method of analysis of airplane and landing gear loads must take into account at least the following elements:
>
> (1) Landing gear dynamic characteristics.
>
> (2) Spin-up and springback ..."

Spin up loads can be calculated as proposed by Transport Canada 523.479 (b) based on NACA T.N.863 simplified analyses (TRANSPORT CANADA, 2002):

$$F_{H\max} = \frac{1}{r_e}\,\frac{\sqrt{2I_w(V_H - V_C)nF_{V\max}}}{t_s}$$

where:

FHmax = maximum rearward horizontal force acting on the wheel (in pounds);

r$_e$ = effective rolling radius of wheel under impact based on recommended operating tire pressure (which may be assumed to be equal to the rolling radius under a static load of n_jW_e) in feet;

Iw = rotational mass moment of inertia of rolling assembly (in slug feet);

VH = linear velocity of airplane parallel to ground at instant of contact (assumed to be 1.2 V_{SO}, in feet per second);

VC = peripheral speed of tire, if pre-rotation is used (in feet per second) (there must be a positive means of pre-rotation before pre-rotation may be considered);

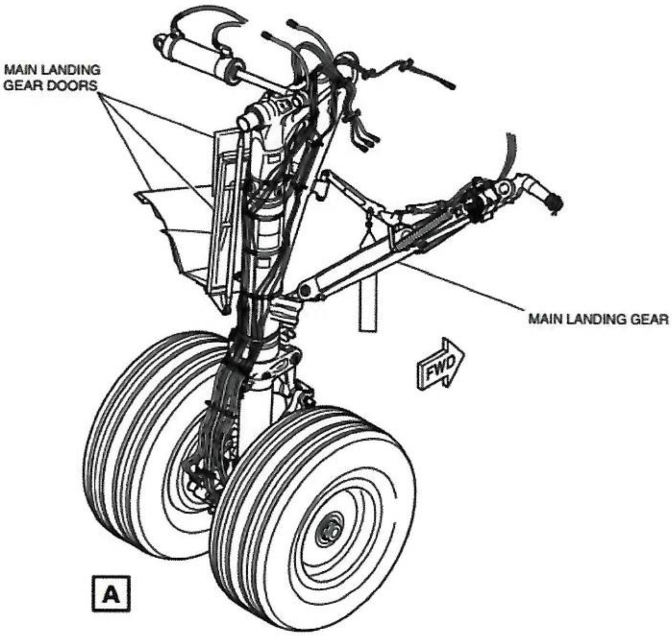
n = effective coefficient of friction (0.80 may be used).

Fv max = maximum vertical force on wheel (pounds) = $n_j W_e$, where W_e and n_j are defined in 523.725;

ts = time interval between ground contact and attainment of maximum vertical force on wheel (seconds). However, if the value of F_{Vmax}, from the above equation exceeds 0.8 F_{Vmax}, the latter value must be used for F_{Hmax}.)

Figure 13 is intended to provide visualization of the landing gear structure.

Figure 13 - Main landing gear structure



Source: (EMBRAER, 2008a)

Since the time wheel is exposed to acceleration is related to the normal viscous reaction of the damper, spring back load is a function of the damper capacity to absorb the normal load.

Installing the regenerative braking system allow the designer to accelerate wheels before touchdown to ground speed, not only saving tire wear but also reducing spin up loads to zero permitting the designer to choose a damper characteristic that can better absorb normal loads leading to lighter landing gears.

5.9 Weight penalty

Weight penalty is surely the major drawback of a regenerative system installation. Additional weight is a huge drawback to any aircraft design as it reduces loading capacity for a given airplane and increases fuel burn as more lift is required.

Based on current state-of-the-art motors, batteries and controllers and systems requirements chapter, components weight can be estimated to be under 1000kg.

Contradicting popular belief, battery is not the heaviest component and would weight close to 200kg based on 200Wh/kg energy density. Motors, couplings and controllers are components which must be carefully designed for weight reduction. It is clear the weight penalty is estimated based on systems and components which were not created to perform under the specific conditions of regenerative braking for aircrafts. Most likely, the development of proper systems, optimized for the given extreme power and short duration will lead to lower weight systems reducing weight penalty.

Offsetting weight by adding capabilities is one of the main form to reduce the additional weight impact. However, considering the all structure is constructed to resist to the loads these components generates it is hard to estimate precisely the weight reduction of each item.

The first and obvious added functionality is braking. Embraer ERJ-190 brake system architecture can be described as shown in Figure 14:

The installation of regenerative brakes in two of the four wheels permits the removal of two brake assemblies, two shutoff valves, two brake control modules, one hydraulic fuse, one hydraulic accumulator, four hydraulic lines and of course hydraulic fluid. These components are estimated to weight 140kg.

The APU and APU generator including all cabling and installation accessories are estimated to weight 150kg.

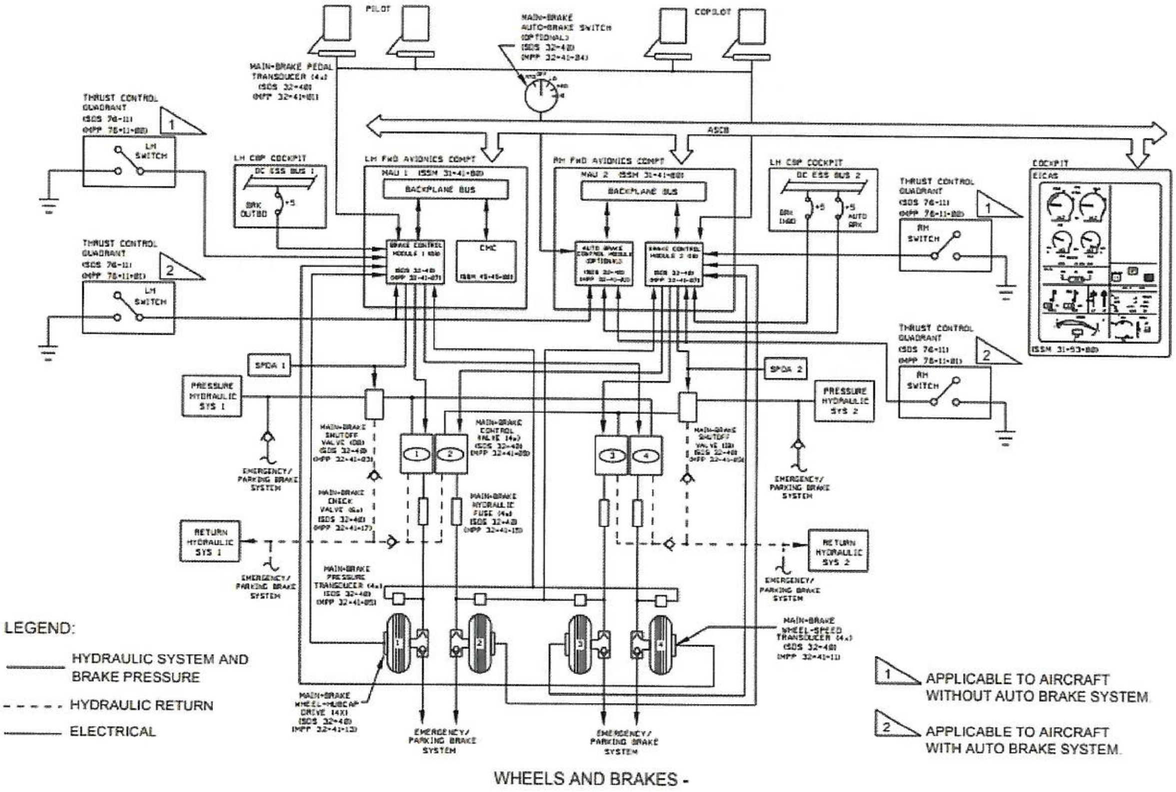
The Ram Air Turbine actuating system, supports, cables and the turbine itself is estimated to weight 60kg. The two NiCd batteries add to their supports and baling are estimated to weight 70kg.Other backup batteries may also be removed in order to save weight as emergency lights batteries and flight control backup battery if applicable.

Finally, the reduction in fuel burn of 182kg as a result of the electric taxi capacity also helps offsetting the weight. The estimated weight penalty is lower than 350kg. Considering

Embraer ERJ-190 zero fuel weight is approximately 28000kg and MTOW is 52000kg the installation of this system reduces 1.5% the total load capacity.

Considerations on landing gear weight reduction and structures weight reduction due to removal of components were not considered. It is to be noted the removal of components also reduces the amount of required space which may be used to remove or reduce wing to fuselage fairings which reduces drag and weight.

Figure 14 - ERJ-190 brake system architecture



Source: (EMBRAER, 2008a)

5.10 Certification

Certifying any new system is always a risk for any aircraft manufacturers. Apart from performance the system must prove to be reliable and safe. Certifying this system to be the only braking source was considered not to be appropriate, at least before some maturity is gathered, as FAA25.1309 states the failure must be improbable. In addition, since regulations states the system must perform in all envelope range it is mandatory for it to be either bench and flight tested in multiple scenarios as cold and hot soaks.

Failures during operation may lead aircraft on ground (AOG) and late departures since takeoff and landing capacity is compromised. In case brake system or the regenerative brakes fail (one system inoperative), the operation is addressed via Quick Reference Handbook (QRH) (EMBRAER, 2008b) which provides emergency procedures and operational data for landing the aircraft, as shown in Figure 15.

Figure 15 - QRH reference for brake fail

BRK LH (RH) FAIL

NOTE: Thrust reverser may also be used to stop the airplane.

During landing run gradually apply the normal brake, using rudder pedals to steer the airplane.

Landing configuration:

Slat/Flap.. FULL

Set $V_{REF\ FULL}$.

CAUTION: MULTIPLY THE FULL FLAPS UNFACTORED LANDING DISTANCE BY 1.51.

END

Source: (EMBRAER, 2008b)

Note substantial runway length increase is required. Since V_{REF} is dependent on weight this may be required to be lowered so landing is possible.

5.11 Cost

Acquisition cost is not considered in this scope as it is strongly related to business plans. In general, performance gains in aircrafts are easily paid back by either reducing time between cycles or saving fuel costs.

The Results section in this document provides the simulation results for the performance with regenerative brake system installed. Fuel, ground time and emissions can be easily quantified in money, so the cost of a viable system can be determined.

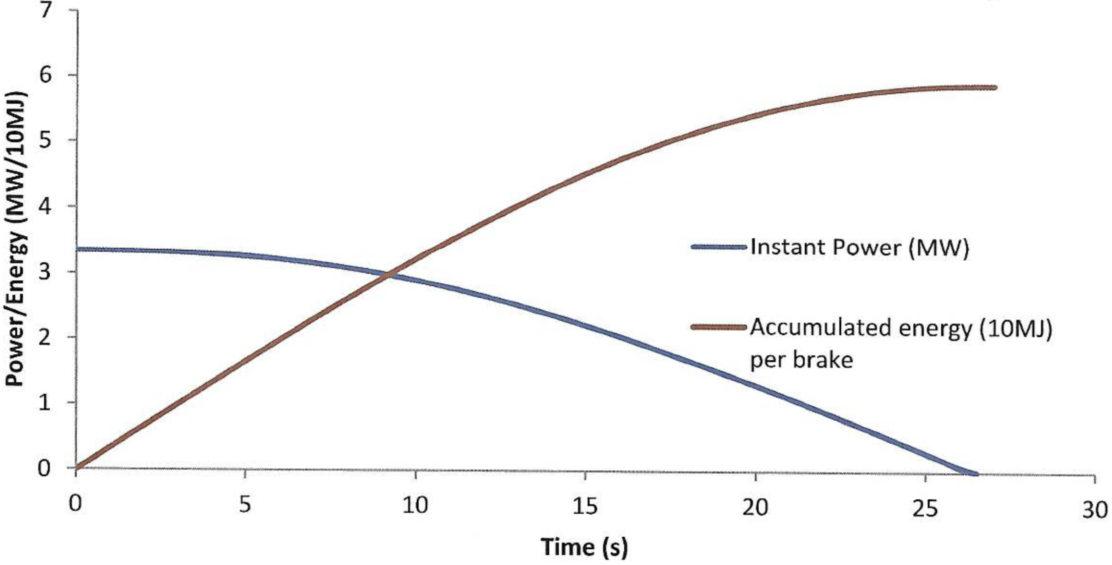
6 AIRCRAFT REGENERATIVE BRAKE SYSTEM REQUIREMENTS

Embraer ERJ-190 may accommodate up to 114 seats in accordance with its Type Certification Data Sheet and is qualified for maximum takeoff weight (MTOW) of 51800kg.

It is mandatory for a regenerative brake system to outperform current brake system if analyzed from the perspective of power and energy. Operations at high temperature and altitude are considered to as ISA+20 13500ft. This condition represents some airports as Aeropuerto Internacional El Alto (ICAO SLLP) which serves the city La Paz, Bolivia, built at 13323ft, average high temperature of 15C.

Such conditions led Embraer ERJ-190 to the largest V_1, which energy is equivalent to the demonstrated (179kt ground speed and 55752kg). In this case, kinetic energy to be absorbed by brakes, after subtracting drag and adding engine spool down energy is roughly 232MJ. This amount must be distributed in 4 wheels so 58MJ is the energy each brake must absorb. The graphic in Figure 16 describes the accumulation of energy by a single brake installed at Embraer ERJ-190 during a maximum brake energy demonstration. Additionally, the graphic displays the instant power this brake was subject.

Figure 16 - Maximum brake energy - Instant power and accumulated energy



Source: Author

It is observable that deceleration process lasts for 26s and the energy accumulation estimative is very close to real energy accumulation (54,4MJ). Moreover, it is possible to observe that the brakes absorbed a nearly constant power of 3.2MW for 5s decaying as speed reduces. This effect is manly due wing lift effect that reduces normal load on main landing gear, reducing braking capacity when airspeed is high.

Whenever this huge amount of energy is absorbed by brake disks, its dissipation causes tires to overinflate, landing gear components and wheels to overheat causing permanent damage. FAA FAR 25.735 (e) 2 states:

> "(2) Maximum kinetic energy accelerate-stop. The maximum kinetic energy accelerate-stop is a rejected takeoff for the most critical combination of airplane takeoff weight and speed. The accelerate-stop brake kinetic energy absorption requirement of each wheel, brake, and tire assembly must be determined. It must be substantiated by dynamometer testing that the wheel, brake, and tire assembly is capable of absorbing not less than this level of kinetic energy throughout the defined wear range of the brake. The energy absorption rate derived from the airplane manufacturer's braking requirements must be achieved. The mean deceleration must not be less than 6 fps2." (FEDERAL AVIATION ADMINISTRATION, 1964)

For this reason, the maximum brake energy is used only in events of emergency where the unlikely yet possible combination of a reject takeoff at maximum takeoff weight and maximum V_1 occurs. On the other hand, EASA regulations describe the Quick Turn Around (QTA) requirement which requires the wheel, tire and braking system to endure a test in which the operator lands the aircraft at the maximum landing weight, taxis for 3 miles with intermediate stops, loads the aircraft with passengers, taxis for 3 miles.

The combination of these two regulations lead brake design to operated regularly up to QTA energy while maintaining capability to absorb maximum kinetic energy in emergency situations. The same approach is assumed for a regenerative brake system. So, battery capacity is determined by maximum brake energy summed to stored energy, limiting operation in casa stored energy is higher than minimum. However, for longevity analyses a typical landing profile must be assumed when energies are lower than QTA.

Because this research focuses on an impact study of such system installed on a commercial regional jet it is assumed the same energy level current brakes are subject: 58,6MJ/wheel for maximum brake energy and 34MJ/wheel for regular operation.

In addition, FAR25.735 states:

> "(1) If any electrical, pneumatic, hydraulic, or mechanical connecting or transmitting element fails, or if any single source of hydraulic or other brake operating energy supply is lost, it is possible to bring the airplane to rest with

> a braked roll stopping distance of not more than two times that obtained in determining the landing distance as prescribed in §25.125." (FEDERAL AVIATION ADMINISTRATION, 1964)

It is evident the need to have at least a dual, independent, battery and brake controller system if this is to be the only braking device. In addition, failure of both systems must be extremely improbable (not more probable one in a billion expositions) as FAR25.1309(b)(1):

> "...(b) The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that—
>
> (1) The occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and..." (FEDERAL AVIATION ADMINISTRATION, 1964)

Alternatively, using the regeneration system in one of the two existing wheels at each main landing gear leg while maintaining carbon brake disks on the other two is more adequate. This configuration would be even more interesting considering costs, weight penalty and the fact that a whole new system as this is prone to failure during operation on conditions not fully analyzed by this document as icing and others.

For these reasons, in this research a mixed solution of carbon disk brakes and regenerative brake system is chosen for analysis, one at each wheel in the same landing gear leg.

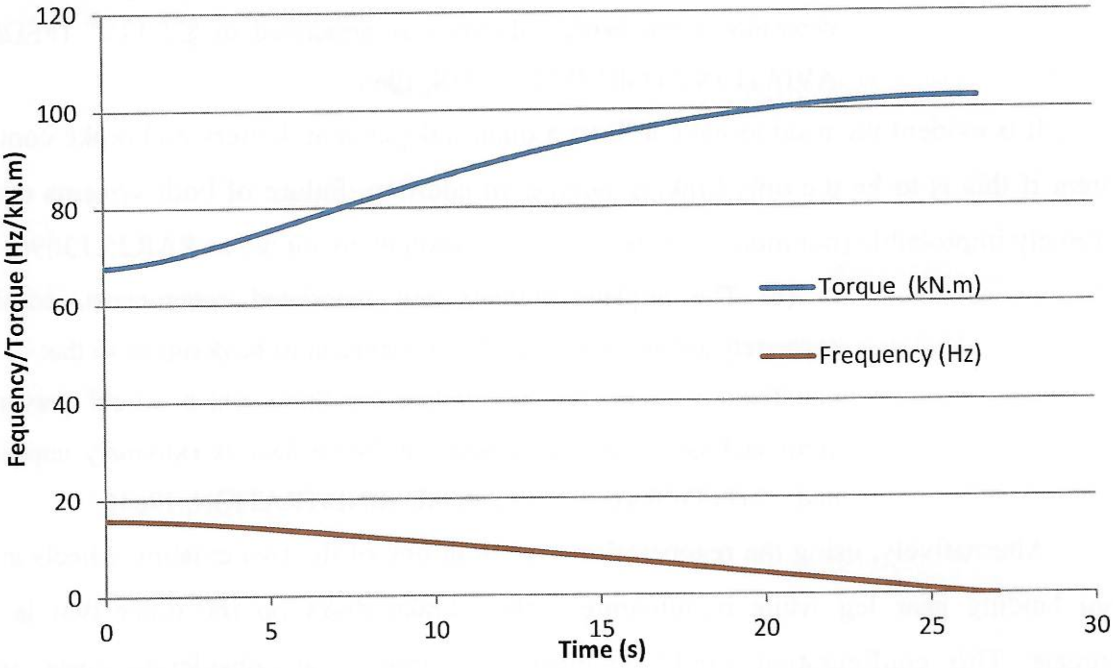
The following sections present a breakdown of the regenerative braking system, as described in the introductory chapter of this dissertation.

6.1 Motors/Generators

Generators must be capable to absorb braking energy during deceleration and since they are linked to the main wheels it is important to know the torque and frequency they will be subject to. Figure 17 displays these parameters as measured during the maximum kinectic brake energy test.

Torque increases as speed frequency decreases. This is not a problem for electric motor as maximum torque is available at stall. On the other hand, even when speed is high, frequency is below 20Hz which can lead to inefficient motors. For this reason, a multi-generator and a gearbox/clutch will most likely be required.

Figure 17 - Maximum brake energy - Main landing gear torque and frequency



Source: Author

6.2 Battery

Battery energy capacity is determined by the capacity to absorb Maximum Brake Energy summed to the minimum energy for operation or storage, in this case 118MJ (32.8kwh).

In addition, battery charge capacity is determined by the operation of both generators producing energy at their higher rates (3.5MW each). Discharge capacity however is not considered as a limiting factor as the capacity for discharging is usually much superior than accumulation.

Capacity however, is a compromise between weight and functionalities. In case the Ram Air Turbine is to be replaced it is important to consider that this system is able to provide 15kVA.Since the RAT may be used during an ETOPS certification this load should be computed. A similar approach should be done in case the APU is to be replaced. ERJ-190 APU is equipped with a 40kVA generator and is also able to provide pneumatic power to the aircraft. The energy consumption of pressuring air for the environmental control must also be accounted.

Battery voltage however is a compromise between generator/motor capacity and efficiency. However, according to ZVEI Voltage Classes for Electric Mobility (FISCHER;

DORN, 2013), protection levels increase substantially if voltage is higher than 1500V. Taking protection level as a deciding factor, most electric vehicles are powered by batteries in 400V range, eliminating the need for special tools, training or protections. Unfortunately, powering the regenerative system with 400V would lead to currents as high as 9000A which are unpractical as cables and motor weight are highly dependent on current.

Considering operational safety and demand for equipment the maximum voltage should be 1500V. Operating at this value currents would be close to 2400A which are not very distant from equipment currently in use for starting aircraft engines.

Apart from performance batteries as any other component must sustain failure and not compromise other systems as per FAR 25.1309(b) (2):

> "...(b) The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that—
>
> (1) The occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and
>
> (2) The occurrence of any other failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions is improbable..."

For this reason, thermal runaways must be contained. Actual aircraft NiCd batteries are housed in a steel box, designed to contain their explosions if they occur. Lithium batteries however, are much more energy-dense thus require an adequate housing. National Transportation Safety Board (NTSB) investigation AIR-14-01 (NATIONAL TRANSPORTATION SAFETY BOARD, 2014) on Japan Airlines incident in 2013 concludes cell-to-cell thermal runaway, unproperly addressed by Boeing Co, has led to smoke and fire in the aircraft while parked on ground. On January 2013, other events concerning this same battery made the American aviation authority FAA to ground all Boeing 787 (FEDERAL AVIATION ADMINISTRATION AVIATION SAFETY, 2013) leading a process on other authorities (total of 50 aircrafts) that would end only four months later in April 2013 (BROWN, 2013).

The ability to maintain the regeneration system safe and able to operate even on a battery failure scenario may require the designer to create multiple battery packs instead of one, differently from the automotive industry. It becomes obvious a battery management system is also required, however this will not be integrally developed in this research. This solution increases complexity, costs and the weight penalty of installing regenerative brakes and in likely to be one of the most important decisions during design phase.

7 MODEL

This section makes full use of Embraer SA proprietary information to provide accurate results and reasonable system evaluation, under company authorization.

Even though takeoff may seem a simple maneuver, it is full of variables and optimizing its parameters is crucial for performance. Takeoff modeling is required for calculating the exact amount of additional energy to be input by wheels. For this reason, take-off run and climb modelling is divided in three parts: ground from 0kt to rotating speed, rotation and initial climb during which landing gear is being retracted and obstacle clearance.

In general lines, the aircraft is accelerated until V_1 is reached. As previously stated V_1 can be as low as V_{MCG} plus the speed attained 1s after V_{EF} or as high as V_R depending on the compromise being made. At V_1 the aircraft may either be decelerated to full stop or accelerated to V_R. In case a reject takeoff is commanded, a braking performance model is used to calculate the braking distance.

After V_1 is reached, for further calculation purposes, an engine is considered to fail (V_{EF}) and the takeoff maneuver will continue. As the aircraft accelerates with a single engine added to the spool down traction of the failed the engine, V_R is reached. Note large differences between V_1 and V_R may lead to long single engine acceleration periods while small differences lead to long accelerate/stop distances.

At V_R the aircraft is pitched up and rotates while accelerating to lift-off speed (V_{LOF}). In general, rotation time is insensible to aircraft weight as it is normally commanded to pilots' discretion to target pitch angle while speed and distance are not. The aircraft is then flown at a target pitch and optimal sideslip angle and after positive rate of climb is sensed by the crew the landing gear is commanded up. Speed increases as the aircraft climbs to V_2 which should be optimized to be the speed at which climb gradient is maximum, if required. It is important to notice that V_2 should not be lower than the minimum control speed in air as described at 25.107:

> "(c) V_2, in terms of calibrated airspeed, must be selected by the applicant to provide at least the gradient of climb required by §25.121(b) but may not be less than—
>
> (1) V_{2MIN};
>
> (2) V_R plus the speed increment attained (in accordance with §25.111(c)(2)) before reaching a height of 35 feet above the takeoff surface; and
>
> (3) A speed that provides the maneuvering capability specified in §25.143(h)." (FEDERAL AVIATION ADMINISTRATION, 1964)

Ideally the aircraft is pitched up in order to reach V_2 at 35ft. At limit cases, the aircraft must be over the runway threshold at half the distance between liftoff and at 35ft high position as on 25.111

> (c) During the takeoff path determination in accordance with paragraphs (a) and (b) of this section—
>
> (1) The slope of the airborne part of the takeoff path must be positive at each point;
>
> (2) The airplane must reach V_2 before it is 35 feet above the takeoff surface and must continue at a speed as close as practical to, but not less than V_2, until it is 400 feet above the takeoff surface;..." (FEDERAL AVIATION ADMINISTRATION, 1964)

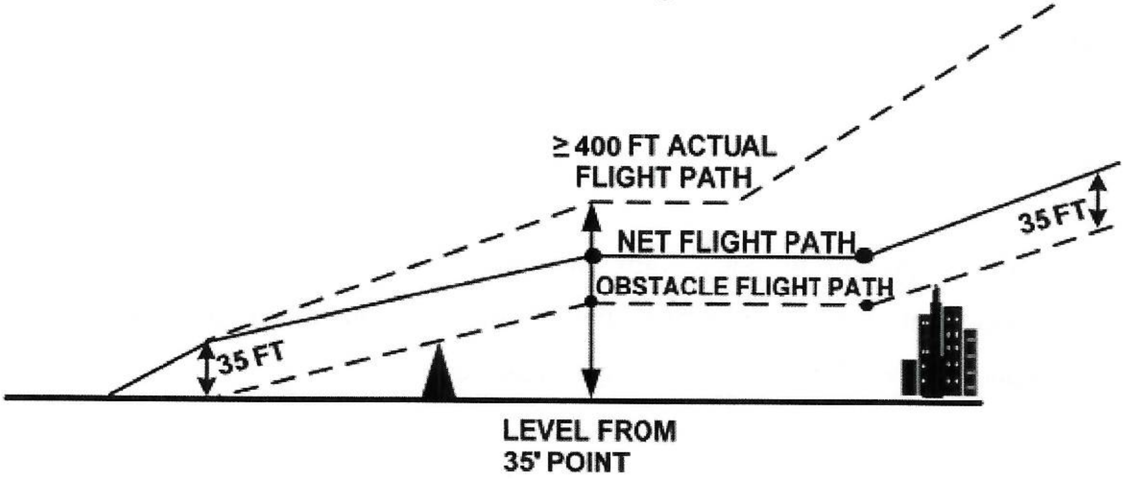
Whenever landing gear is completely retracted, second climb phase starts. At this phase, the aircraft must be able to climb over any near obstacle considering its actual climb capability diminished by 0.8% as stated in requirement 25.121

> "(b) *Takeoff; landing gear retracted.* In the takeoff configuration existing at the point of the flight path at which the landing gear is fully retracted, and in the configuration used in §25.111 but without ground effect:
>
> (1) The steady gradient of climb may not be less than 2.4 percent for two-engine airplanes, 2.7 percent for three-engine airplanes, and 3.0 percent for four-engine airplanes..." (FEDERAL AVIATION ADMINISTRATION, 1964)

The AC25-7C (FEDERAL AVIATION ADMINISTRATION, 2012) explains net takeoff flight path and illustrates the concept as in Figure 18:

> " (a) The net takeoff flight path is the actual flight path diminished by a gradient of 0.8 percent for two-engine airplanes, 0.9 percent for three-engine airplanes, and 1.0 percent for four-engine airplanes.
>
> (b) For the level flight acceleration segment, these prescribed gradient reductions may be applied as an equivalent reduction in acceleration in lieu of reduction in net flight path."

Figure 18 – Net Takeoff Flight Path



Source: Figure 14-2 in (FEDERAL AVIATION ADMINISTRATION, 2012)

This analysis would not be completed if compliance to 25.1001 is not demonstrated. In this case, an aircraft must be able to land 15min after taking off from a given airport at the same runway:

> "(a) A fuel jettisoning system must be installed on each airplane unless it is shown that the airplane meets the climb requirements of §§25.119 and 25.121(d) at maximum takeoff weight, less the actual or computed weight of fuel necessary for a 15-minute flight comprised of a takeoff, go-around, and landing at the airport of departure with the airplane configuration, speed, power, and thrust the same as that used in meeting the applicable takeoff, approach, and landing climb performance requirements of this part." (FEDERAL AVIATION ADMINISTRATION, 1964)

For this reason, the braking performance model must also be able to calculate braking performance for landing conditions. In case this requirement is unattainable with fuel burn and braking performance, some aircrafts as Boeing 747 are equipped with a fuel jettison system. Embraer 190, however, does not have a fuel jettison system so landing at nearly MTOW is required.

For a given weight, takeoff may be limited by each phase being its incapacity to accelerate to V_1 and stop within thresholds, or incapacity to climb to 35ft and maintain minimum climb gradient or the incapacity to climb over a given obstacle. Since all parameters are usually stressed to maximum performance it is common to be limited by one of these factors but to be marginal in other. In addition, performance calculations take ambient conditions into consideration so restrictions may change depending on the environment.

The most obvious and usually critical variable is rain. Wet runways braking coefficients are not usually measured during flight test campaign but rather assumed to be as suggested 25.109. Grooved runways however may significantly reduce performance losses under wet conditions and at the certification applicant choice performance maybe measured in a grooved, wet runway.

It is important to notice how intricate takeoff variables are and that some are uncontrollable in order to understand that a single contribution on the aircraft may increase performance by very little if not carefully calculated.

The three takeoff phases are divided and presented below as individual modules exposing the main variables and how constants were obtained for the Embraer 190. These modules then interact to calculate the actual takeoff performance.

7.1 Accelerate/Stop modelling

The proposed model takes into consideration forces actuating as traction and retarding forces. Traction forces are the engine thrust and a runway slope if applicable. Retarding forces are aerodynamic drag, rolling drag (account for lift) and wheels rolling inertia.

Aircraft's measured acceleration is used for calculating the summed traction forces. Measured dynamic pressure is used to calculate drag and lift.

During braking action of a reject take-off, interacting forces are the same as during acceleration; however, one must notice the engine will spool down from take-off thrust to idle, ground spoilers will deploy, and the brake control module produces different braking coefficients for different speeds.

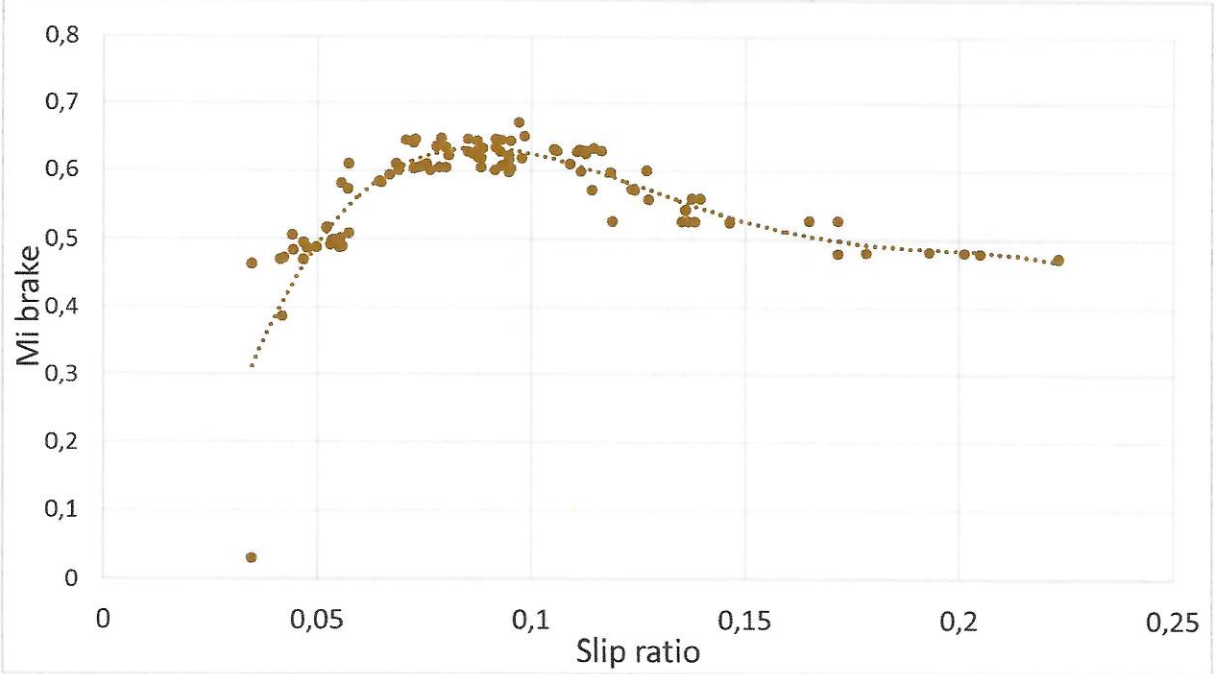
In this case the normal load is calculated including all spoilers' transients and actual lift and weight distribution. The CG height is also taken into consideration as it significantly reduces the load at the main wheels. Then, the deceleration is measured by means of flight test instrumentation. The deceleration force is the sum of all contributing forces. Once drag, slope and engine contributions are computed, the braking force is obtained which, divided by the normal load, is the instantaneous tire-to-asphalt braking coefficient. The distance balanced average of this value is the braking coefficient which can be used to calculate braking performance.

In order to match a model to flight test data the following variables must be of known value:

- Lift and drag coefficients at the takeoff and landing condition. Since most wind tunnels cannot precisely determine these values due to wall interference, these values are determined by a series of unbraked runs at each configuration of flaps where the deceleration is a result of drag, slope and idle thrust.
- Engine thrust. Engine thrust is usually measured by wind tunnel and flight tests by exposing the engine to different airspeeds, air densities and engine fan rotation speeds. Note these parameters are easy to measure at both, wind tunnel and the flight test aircraft.
- Spool-down time. The flight test data of a reject takeoff can be used to determine spool-down time for a given situation and in possession of airspeed, engine fan speed and air density the spool-down traction thrust can be accurately calculated.

In order to evaluate the brake control module efficiency, the slip ratio and its relation to braking coefficient has to be assessed during the deceleration phase. The slip ratio is the quotient of the aircraft wheel speed, for each wheel, divided by the inertial ground speed, as proposed by Currey (CURREY, 1988). If the instantaneous braking coefficient is related to wheels slip rate average a maximum the curve below is obtained as in Figure 19.

Figure 19 – Mi brake as a function of slip ratio



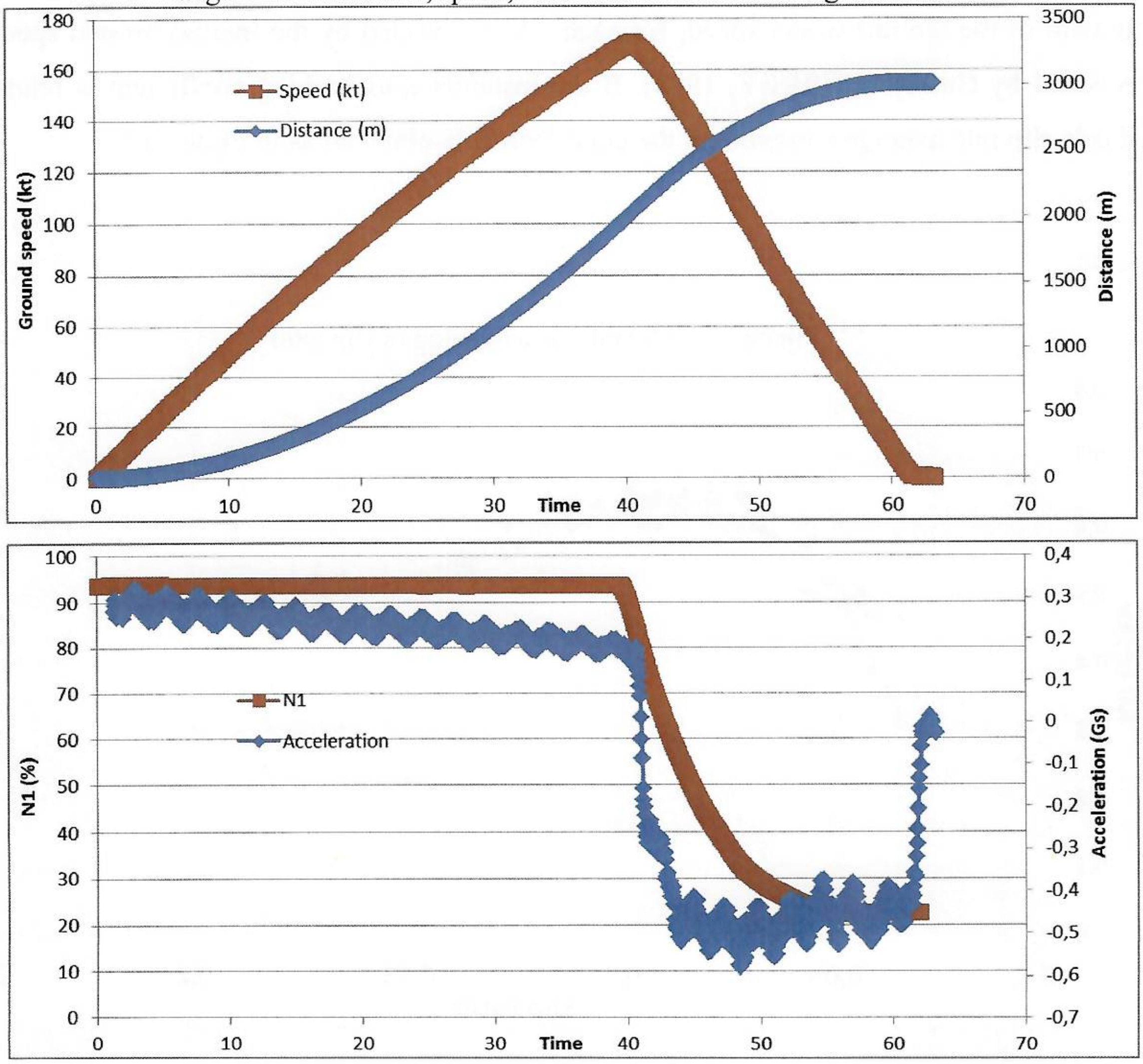
Source: Author

It is clear the braking coefficient increases with slip ratio up to maximum value and then decreases as slip ratio increases. The brake control module uses this data to process the brake control valve command. In case more accurate data is required to evaluate the braking control module, this analysis should to be done at speed intervals rather than the full speed range as tire-to-asphalt braking coefficients change with speed.

This model does not aim to model the brake control module since its performance translates into braking coefficient value directly. The previous analysis however, is a good indicative of how the system behaves and if any failure is present during flight test.

Embraer ERJ 190 maximum kinetic energy braking test was conducted in 2006 for a new tire certification and reported to ANAC at report 190LGR030. Figure 20 exhibits ERJ behavior in this test.

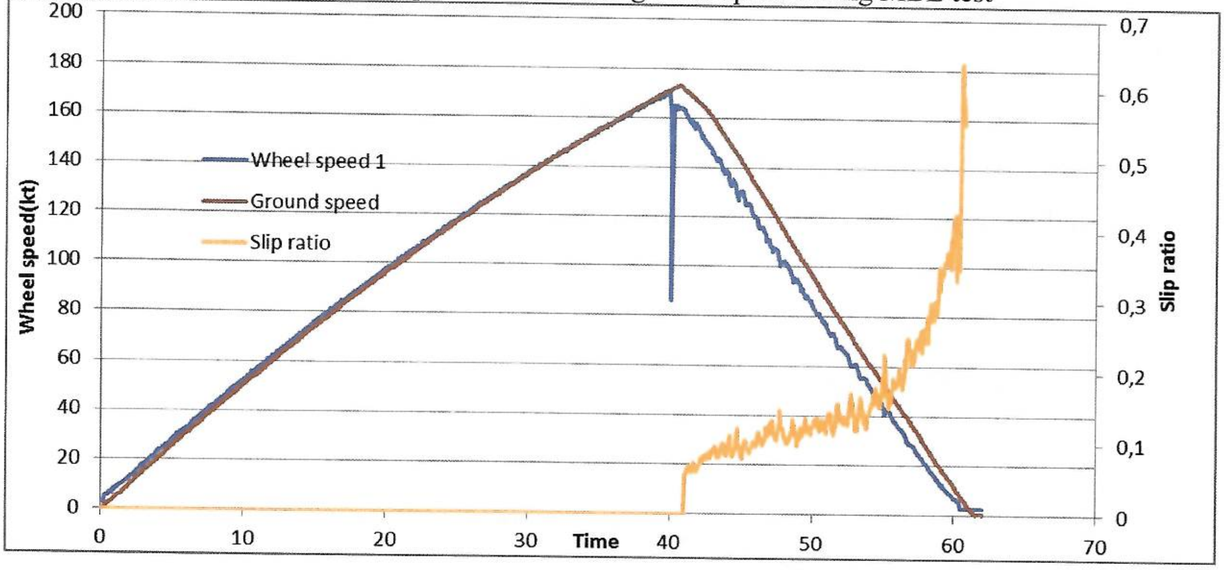
Figure 20 – Distance, speed, acceleration and N1 during MBE test



Source: Author

In order to analyze braking performance, the following graphic is plotted for each wheel (wheel 1 only is shown for clarity in Figure 21)

Figure 21 – Slip ratio, wheel and ground speed during MBE test



Source: Author

The difference between ground speed and wheel speed is used to calculate the slip ratio. Slip ratio in this case is crescent and, apart from initial skid, there are no other skids in during brake action. Note slip ratio skyrockets at the end, this is a usual behavior as wheel there is no anti-skid system at very low speeds.

Similar test points as those shown in Figure 21 were performed in for different energy levels and configurations. A simplified constant brake coefficient is obtained by using the braking distance as the result of the integration of a deceleration caused by drag, engine thrust and braking force, where braking force equals the multiplication result of braking coefficient to aircrafts weight. A distribution of braking coefficients with braking energy was plotted and the approximate value of 0.42 was chosen for data expansion.

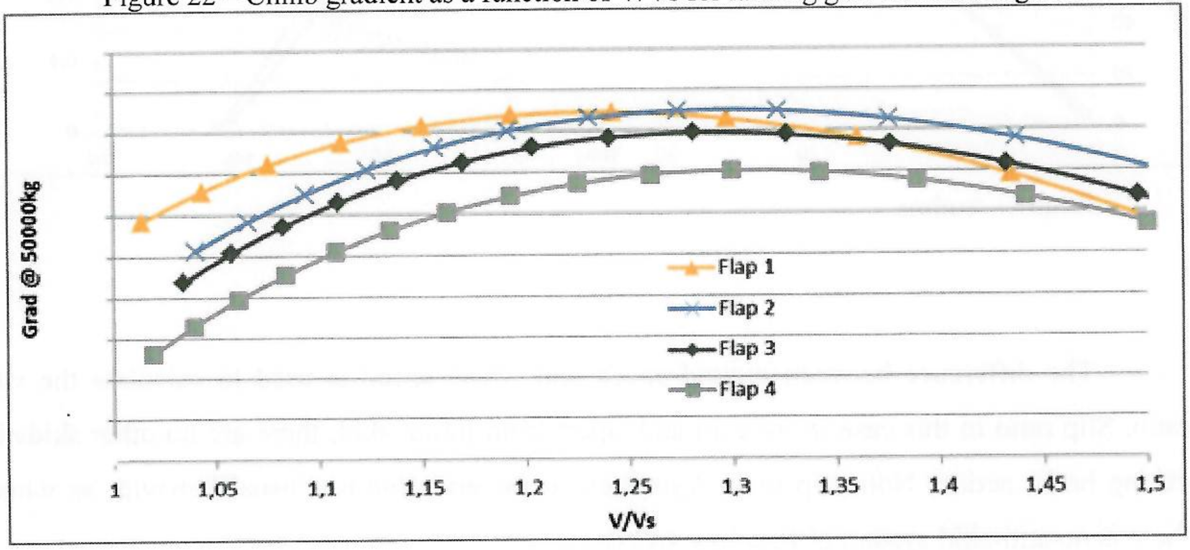
7.2 OEI acceleration and rotation modelling

This segment of the model starts after V_1. The failure of an engine is considered by reducing thrust of one engine as calculated in the accelerate/stop module. The aircraft continues to accelerate to VR, rotates and climbs while retracting the landing gear.

Rotation time is measured and averages 1.3 seconds until V_{LOF} is reached. This time is considered constant for further data expansion.

Climb is then started, and landing gear commanded to retract. Since the quotient between the excess thrust (T-D) and weight is the climb gradient the highest climb ratio is obtained at the lowest possible drag for each flap configuration. For this reason, drag polar and stall speeds flights are performed and constant V_2 to V/V_S is chosen. The peak of the graphic in Figure 22 shows $V_2/\ V_S$ as the highest climb ratio for each configuration.

Figure 22 – Climb gradient as a function of V/Vs for landing gear down configuration



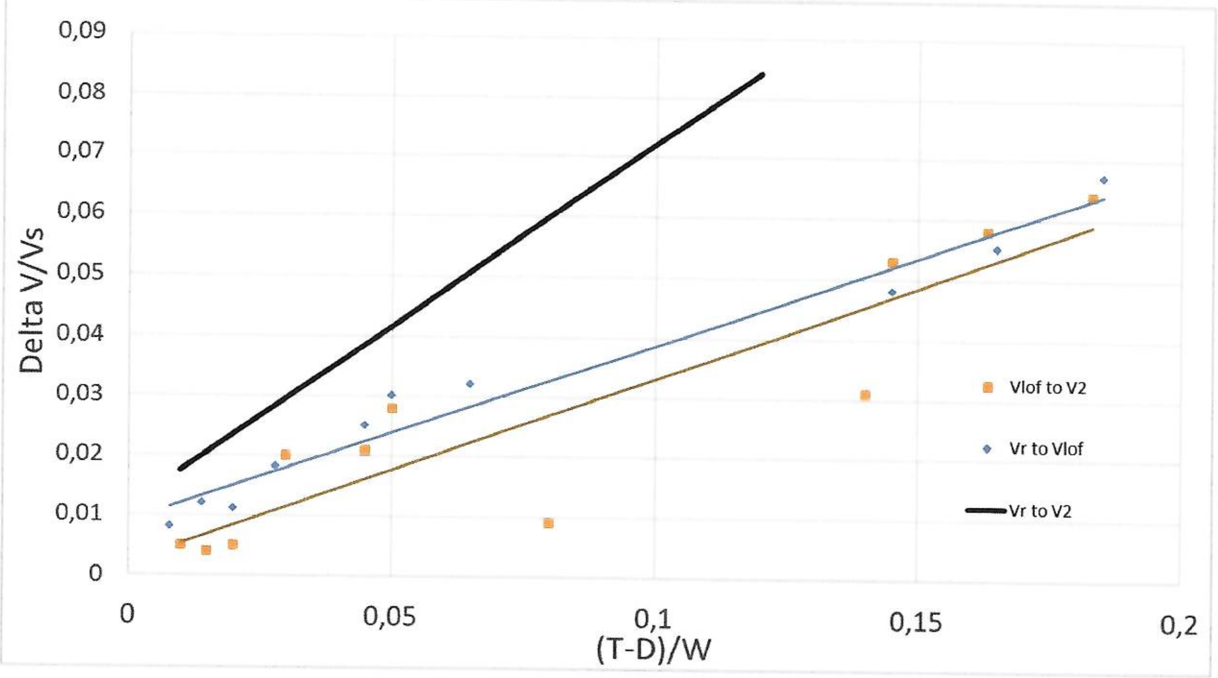
Source: Author

Note that best climb ratio is not the only parameter to choose V_2; balancing short runway performance and limitation as maneuvering margins may determine V_2 at their values. Embraer ERJ-190 considers, at most cases, V_2 equal to 1.18 for flap 1, 1.22 for flap 2, 1.18 flor flap 3 and 1.17 for flap 4.

Ideally, the aircraft should accelerate from liftoff speed to V_2 while climbing to 35ft. Therefore, the proposed modelling will always be adjusted to match this both conditions. Climb continues and finally the landing gear is completed retracted. Since V_2 has being maintained, the climb gradient increases as the landing gear is retracted. Considering the landing gear retraction time is constant if the total energy of the aircraft (kinetic and potential) is evaluated after liftoff and after landing gear retraction one can conclude the difference to be ability of the aircraft to add energy independent of external factors as wind.

In order to the determine the ratio between V_R and V_2 takeoff are analyzed and the difference between the two speeds are used as parameter after being normalized by climb gradient of each test. First V_R to V_{LOF} is plotted followed by V_{LOF} to V_2 hence the relation between the V_R and V_2 is the sum of both curves. Considering the natural dispersion of takeoff flight test the graphic in Figure 23 was used to relate V_{LOF} to V_2.

Figure 23 – V_R to V_{LOF} speed increase



Source: Author based on data from (VIEIRA, [s.d.])

The speed is maintained throughout the climb as landing gear is retracted and the event is ended. Since it is impractical to measure drag during landing gear retraction and since its drag accretion is function of speed and the retraction time is nearly constant, in this case 6s, this takeoff phase is calculated by energy balance. The increase of speed, height and the drag times the distance is equal to the thrust times the distance. Since distance, thrust, height and speed are measurable during landing gear retraction, the variation in drag coefficient can be calculated and it is used for data expansion.

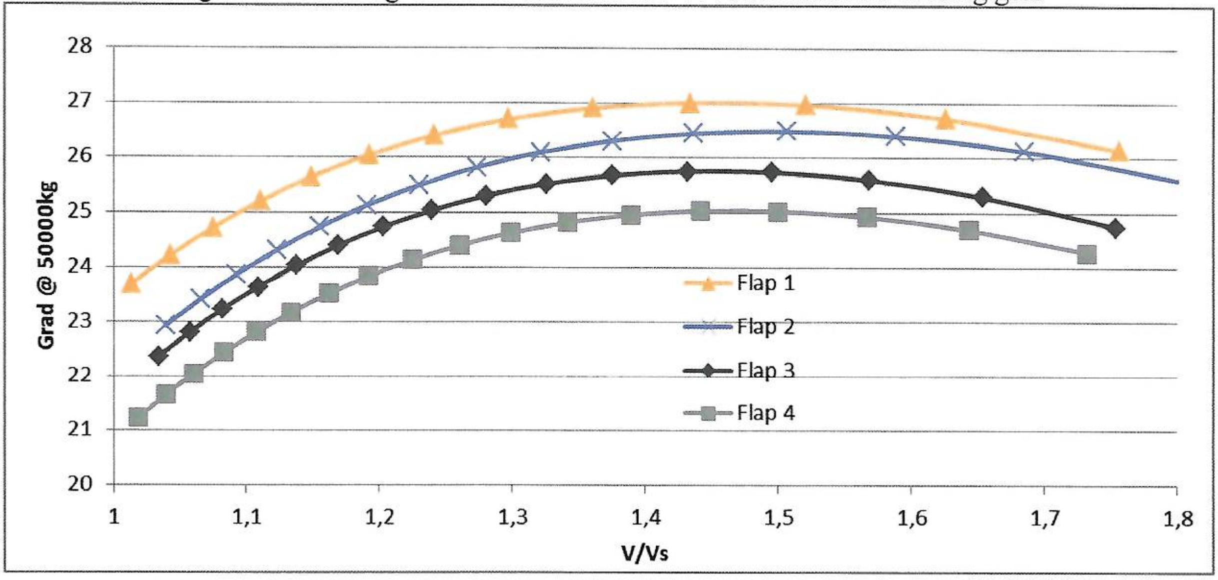
7.3 Second segment climb modeling

Second segment climb modelling starts at the altitude and position where the landing gear was completely retracted and ends at obstacle clearance. This segment of climb is regulated by 25.101.

Since the aircraft is stable at both speed and configuration climb analysis can be performed by comparing the distance to the obstacle and the climb rate diminished by 0.8%. It is essential to determine drag coefficients for this phase for this reason, drag polar and stall speeds flights are performed. Even though best L/D ratio might not be the same from landing gear extended configuration to retracted speeds are not changed and climb is performed at V_2.

Climb is not the focus of this analysis as the proposed system would not affect climb performance for a certified aircraft. It is to be noted however that, as previously stated, the best climb is not the only parameter to choose V_2 and that the best climb rates occur at higher speeds for retracted landing gear configuration as shown in Figure 24:

Figure 24- Climb gradient as a function of V/Vs for retracted landing gear



Source: Author

The introduction of regenerative brakes in any aircraft will demand recalculation of optimal takeoff schedule and it is likely V_2 will be chosen higher.

7.4 Model integration

Once the modeling strategy is clear, it is important to understand how distinct model modules affect each other in order to evaluate design decisions and calculate maximum performance strategy.

Calculations start by defining an airport, weight and flap configuration. All aerodynamic coefficients as CL, CD and maximum CL are imported from the database constructed based on previously described flight tests. Stall speed is calculated and so is V_{MC}, V_2 is than calculates as a function of V_S. Later, climb gradient after liftoff is calculated and V_R is calculated. Finally, V_1 is initially chosen as equal to V_R and the first module is started.

The accelerate/stop module calculates the distance required to accelerate the aircraft and to decelerate to 0kt. In case the distance is larger than the runway length the process is restarted by reducing 1kt at V_1. The process runs until the aircraft can accelerate and stop in the given runway.

The increase of V_1 contributes for the reduction of time and distance to reach V_R since the aircraft is powered by all engines up to V_1 and propelled with an engine failure to V_R. However, the increase of V_1 requires the aircraft to be stopped at higher speeds and less runway availability so for a given runway length and weight, there is a maximum V_1 that can be achieved. Note V_1 has also minimum values as described before.

A pass/fail script is then run and checks if V_1 is larger than V_{1min} if so V_1 is considered valid. If not, the proposed configuration is impossible to operate.

Distance to V_R than calculated using thrust from a single engine added by the spool down thrust of the other engine. The distance is added to rotation distance and, as on 25.107, added to the distance to achieve V_2 and 35ft. The distance value is then compared to the runway threshold and if smaller this part is considered valid.

The pass/fail script is then run and checks if V_R is at least, higher than 1.05Vmc as per 25.107. Climb is also checked after liftoff, and is considered valid if positive.

Note that increasing flap angle (up to a reasonable position) will produce lower Vs and lower climb gradients for the same V/V_S so depending on the limiting factor different flaps will produce higher weight takeoffs.

Finally, the obstacle clearance is checked using the third module, the pass/fail script is run and if the aircraft is unable to clear the obstacle the configuration is deemed impossible.

8 RESULTS

This section presents the simulations results of the matched model for the current certified ERJ-190 and an aircraft of same aerodynamic characteristics with regenerative brakes installed on two of the four main wheels.

8.1 Takeoff performance

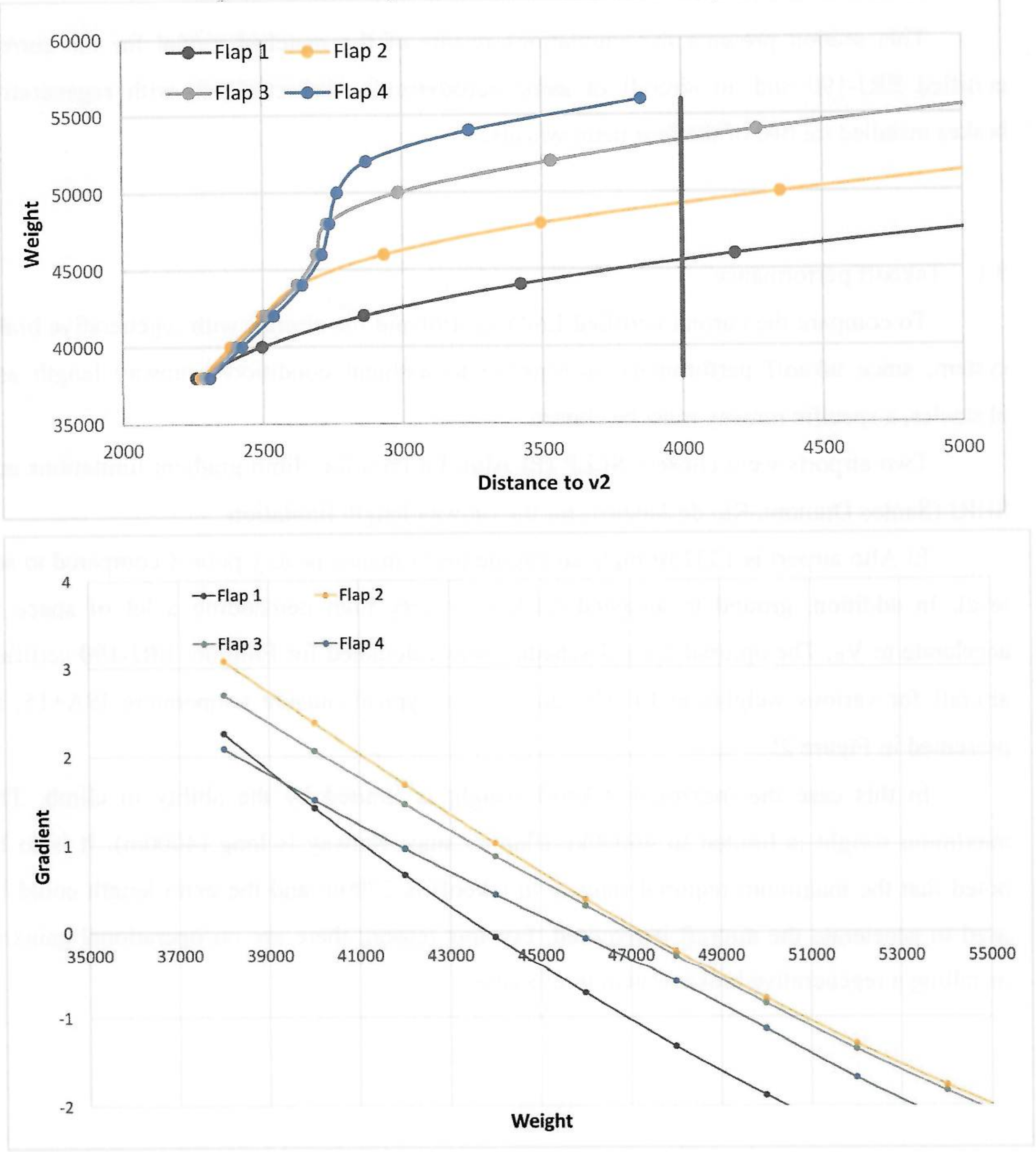
To compare the current certified Embraer 190 and the aircraft with regenerative brake system, since takeoff performance is sensible to ambient conditions, runway length and obstacles, a specific runway must be chosen.

Two airports were chosen: SLLP (El Alto, La Paz) for climb gradient limitations and SBRJ (Santos Dumont, Rio de Janeiro) for the runway length limitation.

El Alto airport is 13323ft high, so engine performance is very poor if compared to sea level. In addition, ground to airspeed relation is very high demanding a lot of space to accelerate to V_R. The optimal takeoff schedule was calculated for Embraer ERJ-190 certified aircraft for various weights at El Alto airport and typical outside temperature ISA+15, as presented in Figure 25.

In this case the maximum takeoff weight is limited by the ability to climb. The maximum weight is limited to 46000kg (flap 2) since runway is long (4000m). It is to be noted that the maximum required runway to takeoff is 2700m and the extra length could be used to accelerate the aircraft if required. For this reason, there are no operational gains in installing a regenerative brake system in this case.

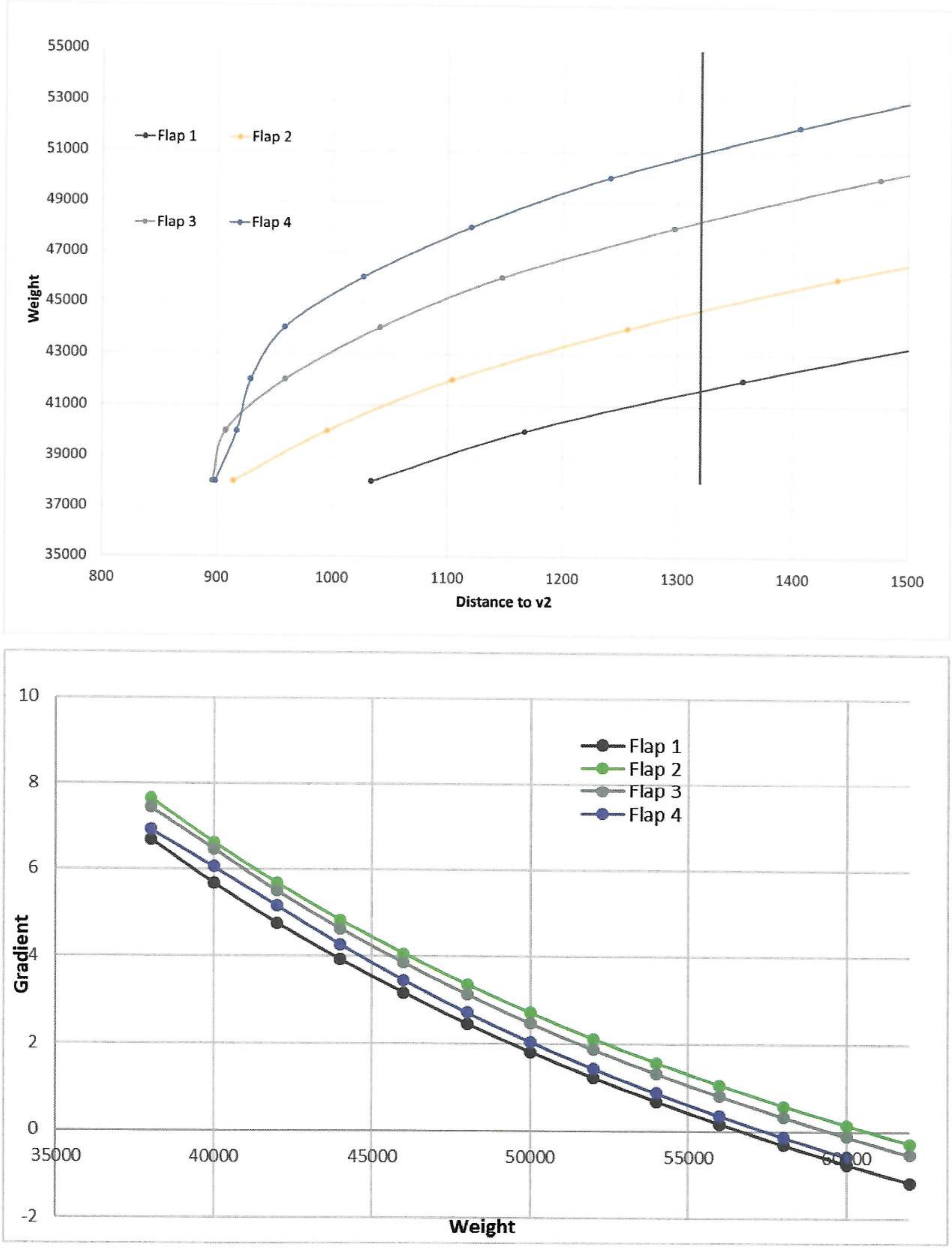
Figure 25 –TO weight vs distance and climb vs weight at SLLP



Source: Author

SBRJ airport has a short runway (1320m) at sea level with close obstacles. Embraer ERJ-190 certified airplane performance for this airport is limited by both runway length and obstacle. Obstacles heights and distances are determined by using official Standard Instrument Departures. Normally a ferry boat antenna in the main obstacle as it is very close to the runway threshold (approximate 70m) and measures 14ft. However, most operators of this airport choose to wait for the boat to pass in order to start the takeoff run so that performance is limited by runway length. Calculated performance for the certified ERJ-190 at ISA+15 for various flaps is represented in Figure 26.

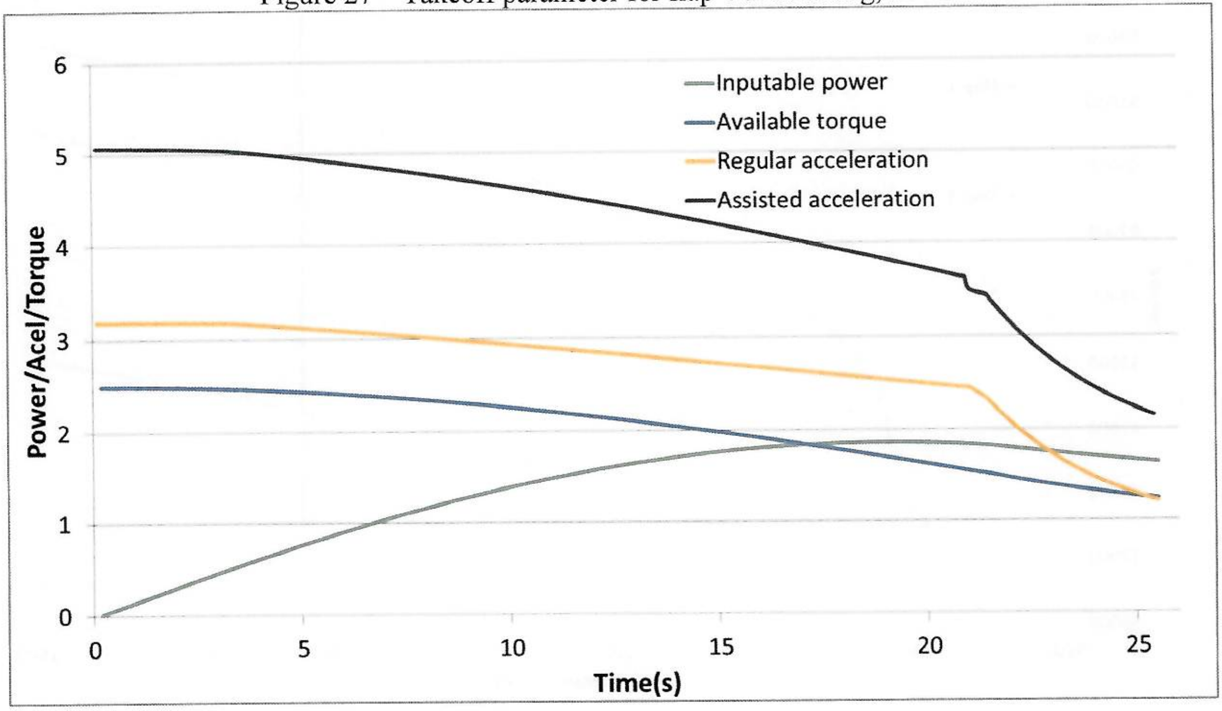
Figure 26 – TO weight vs distance and climb vs weight at SBRJ



Source: Author

If the normal load and torque are calculated for flap 4 at 50000kg the graphic in Figure 27 can be plotted. Note the acceleration difference between regular, engines only, and assisted by two wheels.

Figure 27 – Takeoff parameter for flap 4 at 50000kg, SBRJ

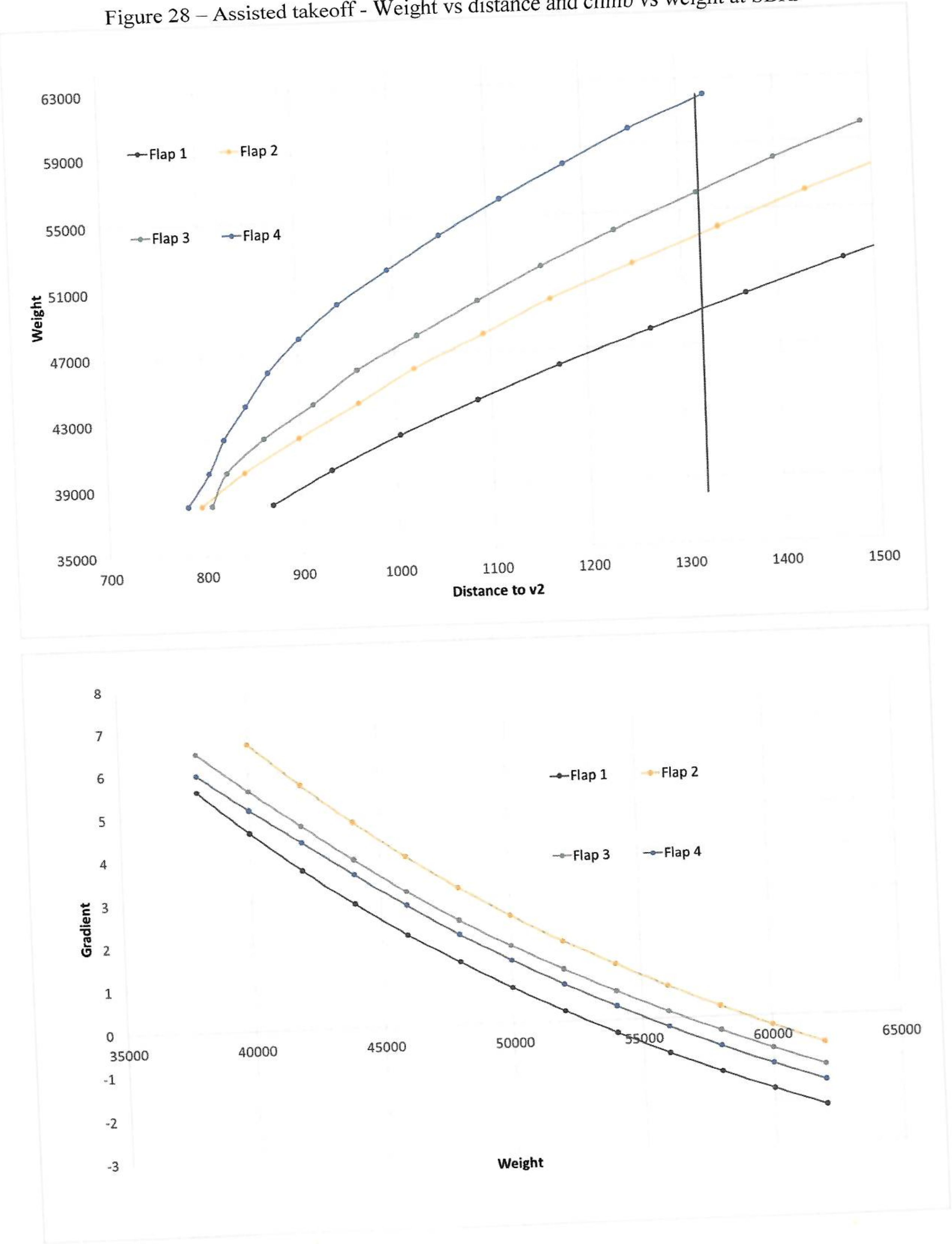


Source: Author

As expected, the power increases with speed but decreases close to V_1. At speeds near V_1 the engine failure effect and lift are appreciable, both reduce normal load at the main landing gear and so the maximum inputable power. On the other hand, acceleration is substantially higher, increased by 58% in average. One can conclude the additional power add by two accelerating wheels is roughly equivalent to another engine during takeoff run. Additionally, power demand is inferior to the power required to brake the aircraft as previously presented. So, motor/generator must be dimensioned to provided braking capability other than takeoff assistance.

A new takeoff schedule is then calculated considering the extra power, as in Figure 28. The distance required to reach V_1 is reduced and so is the distance to V_R as the OEI acceleration is still high.

Figure 28 – Assisted takeoff - Weight vs distance and climb vs weight at SBRJ



Source: Author