ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

AN ALTERNATIVE FUEL ASSESSMENT MODEL FOR SHIPS AND EXPERIMENTS ON THE EFFECT OF METHANOL ON DIESEL ENGINES

Ph.D. THESIS

Burak ZİNCİR

Department of Maritime Transportation Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

GEMİLER İÇİN BİR ALTERNATİF YAKIT DEĞERLENDİRME MODELİ VE METANOLÜN DİZEL MOTORLARDA ETKİLERİ ÜZERİNE DENEYSEL ÇALIŞMA

DOKTORA TEZİ

Burak ZİNCİR
(512142002)

Deniz Ulaştırma Mühendisliği Anabilim Dalı

Deniz Ulaştırma Mühendisliği Lisansüstü Programı

Tez Danışmanı: Prof. Dr. Cengiz DENİZ

EKİM 2019

Burak Zincir, a Ph.D. student of ITU Graduate School of Science Engineering and Technology student ID **512142002**, successfully defended the dissertation entitled **"AN ALTERNATIVE FUEL ASSESSMENT MODEL FOR SHIPS AND EXPERIMENTS ON THE EFFECT OF METHANOL ON DIESEL ENGINES"**, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Cengiz DENİZ** ....
Istanbul Technical University

Jury Members : **Prof. Dr. Ata BİLGİLİ** ....
Istanbul Technical University

Asst. Prof. Dr. Yalçın DURMUŞOĞLU ....
Istanbul Technical University

Asst. Prof. Dr. Aykut SAFA ....
Yildiz Technical University

Asst. Prof. Dr. Görkem KÖKKÜLÜNK ....
Yildiz Technical University

Date of Submission : 16 September 2019
Date of Defense : 16 October 2019

To my family in the present and future,

FOREWORD

When I look back on my Ph.D. journey of 5 years, I am surprised that it passed quicker than I expected and now I prepared my Ph.D. thesis. First of all, I would like to give my appreciation to Prof. Dr. Cengiz DENIZ, my supervisor since from my undergraduate years until now which is about 10 years. He has made critical comments about my thesis study and other academic studies. I would like to thank you for his advises, support, and believe in me during my academic career.

I want to send my gratitude to Prof. Dr. Martin TUNÉR, my supervisor during my stay at Division Of Combustion Engines, Department of Energy Sciences at Lund University, Sweden. I would like to thank you for accepting me to your division and your project group. He made essential comments and gave important advice to me during my experimental studies that widen my perspective and knowledge about the combustion engines, methanol fuel, and experimental studies. Thank you for your kindness and positiveness.

I want to say thank you to Dr. Marcus LUNDGREN, the head of combustion engine laboratory of Lund University for the scheduling of the laboratory and solving problems in the test cell. Also, I want to thank all technicians, especially, Tommy PETERSEN and Anders OLSSON for their efforts to make the engine and test cell equipment ready for the experiments.

The experimental part of the thesis study was financially supported by Lund University and King Abdullah University of Science and Technology under the project named “Sun Fuels for Transportation and Stationary Power” with the participants of Lund University, Chalmers University of Technology, KTH Royal Institute of Technology, Aalto University, and King Abdullah University of Science and Technology.

I want to thank all my friends at ITU Maritime Faculty and Lund University for our good times. Especially, Çağlar DERE and Çağatay KANDEMIR, you are more than a colleague of mine. I hope we will continue our good friendship in the future. Also, I want to say thank to Dr. Pravesh SHUKLA for his friendship and support at my first experiments, and Dr. Sam SHAMUN for his friendship and teaching me the post-processing. Moreover, thanks to Amir Bin AZIZ and Nika ALEMAHDI for their good friendship during my stay in Lund.

Last but not least, I would like to thank my parents and brother. I cannot finish my Ph.D. without their encouragement and support to me. They always make life easier for me to provide me to focus only on my Ph.D. studies. I love you all.

September 2019

Burak ZİNCİR
(Marine Engineer)

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ABBREVIATIONS

AFE : Alternative fuel effect
AHP : Analytic Hierarchy Process
AP : Acidity potential
BC : Black carbon
BMEP : Brake mean effective pressure
BTL : Synthetic biodiesel
Btu : British thermal unit
CA10 : Crank angle at 10% of heat released
CA50 : Combustion phasing
CA90 : Crank angle at 90% of heat released
CI : Consistency index
CN : Cetane number
COV : Coefficient of variation
CR : Consistency ratio
DISI : Direct Injection Spark Ignition
DME : Dimethyl Ether
E85 : Ethanol mixture 85%
ECA : Emission Control Area
ECU : Electronic control unit
EDP : Ecological damage point
EEDI : Energy Efficiency Design Index
EEOI : Energy Efficiency Operational Indicator
EGR : Exhaust Gas Recirculation
ELECTRE : Elimination and Choice Expressing Reality
EOI : End of injection
EP_{TOT} : Total ecology point
ERP : Emission reduction point
EVO : Exhaust valve opening
EWP : Emission weight point
FID : First injection duration
FIS : First injection timing sweep
FuelMEP : Fuel mean effective pressure
GHG : Greenhouse gas
GI : Gas injection
GTL : Synthetic diesel
GVU : Fuel valve train
GWP : Global warming potential
HCCI : Homogeneous Charge Compression Ignition
HFO : Heavy fuel oil
HRR : Heat release rate
HVO : Hydrotreated vegetable oil
ICE : Internal combustion engine

IMEP : Indicated mean effective pressure
IMEP$_g$: Gross indicated mean effective pressure
IMEP$_n$: Net indicated mean effective pressure
IMO : International Maritime Organization
IP : Investment point
IVC : Intake valve closing
LBG : Liquefied biogas
LEL : Lower explosive limit
LGI : Liquid gas injection
LHV : Lower heating value
M85 : Methanol mixture 85%
MARPOL : International Convention for the Prevention of Pollution from Ships
MCDM : Multi-criteria decision making
MCR : Maximum continuous rating
MEPC : Marine Environment Protection Committee
MGO : Marine gas oil
MON : Motor octane number
MP : Maintenance point
MRV : Monitoring Reporting Verification
NATO : North Atlantic Treaty Organization
OECD : Organization for Economic Cooperation and Development
ON : Octane number
PPC : Partially premixed combustion
Prail : Rail pressure
PRF : Primary reference fuel
PRR : Pressure rise rate
QMEP : Heat mean effective pressure
RCCI : Reactivity controlled combustion ignition
RI : Random index
RME : Rapeseed methyl ester
RON : Research octane number
SCR : Selective catalytic reduction
SEEMP : Ship Energy Efficiency Management Plan
SFC : Specific fuel consumption
SI : Single injection
SIS : Second injection sweep
SOC : Start of combustion
SOI : Start of injection
STCW : Standards of Training Certification and Watchkeeping
TDC : Top dead center
TLV : Threshold limit value
UEL : Upper explosive limit

SYMBOLS

A/F_s : Stoichiometric air/fuel ratio
$Ca(OH)_2$: Calcium hydroxide
C_p : Specific heat at constant pressure
C_v : Specific heat at constant volume
r_c : Compression ratio
NaOH : Sodium hydroxide
V_d : Engine displacement volume
η_c : Combustion efficiency
η_{GIE} : Gross indicated efficiency
η_{NIE} : Net indicated efficiency
η_t : Thermodynamic efficiency
λ : Air/fuel equivalence ratio
λ_{max} : Maximum eigenvalue of the matrix
γ : Ratio of specific heats

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AN ALTERNATIVE FUEL ASSESSMENT MODEL FOR SHIPS AND EXPERIMENTS ON THE EFFECT OF METHANOL ON DIESEL ENGINES

SUMMARY

Rise in the amount of emissions worldwide is directly related to energy consumption. World energy consumption was 575 quadrillion Btu in 2015 and it is estimated that it will be 663 quadrillion Btu in 2030 and 736 quadrillion Btu in 2040. Energy is consumed in various areas. These are buildings, transportation, and industry. Buildings consist of residential and commercial structures. Industry consists of production facilities, factories, and heavy industry areas. Transportation contains road transportation, railway transportation, aviation, and shipping. Transportation forms an important portion of the world energy consumption. In 2015, the energy consumed by transportation is approximately 110 quadrillion Btu and it is estimated that it will rise to 140 quadrillion Btu in 2040.

The shipping sector is a major element in worldwide trade. 90% of the world trade, 90% of outer trade of the European Union and 40% of inner trade of the European Union is done by the shipping sector. According to data of European Energy Agency, the shipping sector is the reason for 1.94% of world carbon monoxide (CO) emission, 20.98% of world nitrogen oxide (NO_X) emission, 11.8% of world sulfur oxide (SO_X) emission, 4.63% of world particulate matter (PM10), and 8.57% of world particulate matter (PM2.5). International Maritime Organization states that the shipping sector consumed 300 million tons of fuel in 2012 and emitted 938 million tons of CO_2 emission, 19 million tons of NO_X emission, 10.2 million tons of SO_X emission, 1.4 million tons of PM emission, and 936 thousand tons of CO emission.

International Maritime Organization has worked on to control and reduce the emission amounts from ships. Stricter emission rules and regulations entered into force for decreasing CO_2, NO_X, SO_X, and PM emissions. To cope with these rules and regulations, there are various emission abatement technologies and methods for the shipping sector. These can be exhaust gas recirculation, selective catalytic reduction, reduction with water, and engine modifications for NO_X emissions while SO_X scrubber for SO_X emissions. However, these emission abatement technologies and methods reduce the aimed emission type, they have a neutral or negative effect on other types of emissions, such as CO_2, CO or PM emissions. In addition to these, using alternative fuels on ships is another emission abatement method. There is a potential that alternative fuels can reduce CO_2, NO_X, SO_X, and PM emissions at the same time. Alternative marine fuels can be liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol, ethanol, dimethyl ether, biodiesel, biogas, synthetic fuels, hydrogen, electricity, and nuclear fuel. Nowadays, also, ammonia is considered as an alternative marine fuel. The shipping sector has been heading towards alternative fuels. There are 116 LNG-fuelled ships in operation, 112 new orders, and 93 LNG-ready ships, 2 methanol-fuelled ships in operation and 6 chemical tankers in order, 12 LPG-fuelled gas carriers in operation, 2 ethane-fuelled ships in operation

and 2 ships in order, and 2 hydrogen-fuelled ships are in operation worldwide. The shipping is a unique sector with its special rules, regulations, and implementations. As a consequence, before selecting an alternative fuel for a ship, various aspects should be considered, for instance, the specifications of alternative fuels, maturity of the system, reliability of the fuel, effects on emissions, compliance with the rules and regulations, initial cost, operational costs, etc. Decision-makers use multi-criteria decision-making methods during these kinds of situations.

This thesis study consists of two main sections. The first section is the formation of an assessment model for the selection of alternative fuels for shipboard usage. Various criteria were determined to assess alternative fuels and find suitable ones for shipboard usage. Analytic Hierarchy Process (AHP) was used as a multi-criteria decision-making method with the criteria of safety, legislation, reliability, technical, economy, and ecology. Alternative fuels are used in the study are ammonia, ethanol, hydrogen, kerosene, LNG, LPG, and methanol. The criteria and sub-criteria weightings were determined by getting expert opinions and doing a pair-wise comparison by using the AHP method. The highest weightings were the weightings of safety and ecology criterion with 0.346. The legislation criterion followed them with a weighting of 0.146. The remaining criteria were reliability, technical, and economy with the weightings of 0.090, 0.046, and 0.025, respectively. The pair-wise comparison was done for alternative fuels at each criterion. The final assessment result showed that LNG is the most suitable alternative fuel with the highest weighting of 0.234. The second alternative fuel is methanol with the weighting of 0.151 and the third alternative fuel is ammonia with a weighting of 0.148.

The second section of the thesis study is the experimental study with methanol fuel on a Scania D13 heavy-duty diesel engine. The experimental studies were performed at the laboratory of the Division of Combustion Engines, Department of Energy Sciences at Lund University, Sweden. To burn methanol at the diesel engine, partially premixed combustion concept was applied. The combustion properties, engine performance, and engine emissions were investigated during the experiments. The experiments were done at 2 bar, 3 bar, 5 bar, and 10 bar $IMEP_g$ engine loads. The effect of intake temperature, single injection, split injection, and fuel injection parameters of injection timing, injection duration, and rail pressure were observed under various engine loads. The common finding of the experimental study was the combustion stability, COV $IMEP_n$, was good with 2%. The engine efficiency was between 0.44 and 0.49 and the combustion efficiency was between 0.89 and above 0.99. The CO and THC emissions were high until 5 bar $IMEP_g$ engine load, but then they decreased to 0.2 g/kWh. The NO_X emissions were within the limit of NO_X Tier III until 5 bar $IMEP_g$, but then they rose to 5 g/kWh and 5.5 g/kWh, which are within the limits of NO_X Tier II, at 8 bar and 10 bar $IMEP_g$, respectively. The last study in the thesis was the prediction of specific fuel consumption, engine efficiencies, combustion efficiency, and emissions from 10 bar $IMEP_g$ to 20 bar $IMEP_g$. This was done due to the limitations of the engine operation.

The thesis study showed that the results of the assessment model are in parallel with the reality of the shipping sector and it can be used during the decision-making process for the selection of alternative fuels for ships. The experimental study part of the thesis reveals that methanol can be burned by using partially premixed combustion concept at a heavy-duty diesel engine with good combustion stability, high engine efficiency, and low engine emissions. The sulfur-free structure of methanol results with zero SO_X emission. In addition to this, the short-chain structure of methanol and the combustion property of partially premixed combustion concept achieve almost zero PM emission. The NO_X emission is under Tier III Limits of IMO until 5 bar $IMEP_g$ and it increases after that point. But the NO_X emission can be easily reduced below NO_X Tier III Limits by using exhaust gas recirculation while operating the engine at partially premixed combustion. Methanol has lower carbon content than conventional marine fuels which is an advantage for lower CO_2 emissions. Moreover, if the usage of bio-methanol spreads worldwide, there will be no need to record CO_2 emissions because it is a carbon-neutral fuel. The methanol partially premixed combustion concept complies with the recent CO_2, NO_X, and SO_X rules and regulations.

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ÖZET

Günümüzde, hava kirliliği, küresel ısınma ve iklim değişikliği konuları öncelikli tartışma ve araştırma konularıdır. Paris'teki Birleşmiş Milletler İklim Değişikliği Konferansı'nda imzalanan, bağlayıcılığı olmayan, ülkeler arası anlaşmada belirtilen emisyon seviyeleri ile günümüzdeki emisyon miktarları karşılaştırıldığında, belirtilen seviyenin aşılmış olduğu görülmektedir. Küresel ısınma, atmosfere yayılan sera gazları ile beraber artmaktadır. Karbondioksit, yayılan bu sera gazlarının en önemli ve en fazla yayılan parçasıdır. Küresel ısınma, aşırı yağışlar, fırtınalar, buzulların erimesi, sel veya aşırı kuraklık gibi aşırı doğa olayları ile beraber iklim değişikliğine neden olmaktadır. Küresel ısınmayı yavaşlatmaya yönelik çalışmalar olmasına rağmen, dünyadaki enerji tüketimindeki artış bu çabayı etkisiz hale getirmektedir. İklim değişikliğinin yanında hava kirliliği ve hava kalitesinin bozulması da insan sağlığını ve ekim alanlarını etkileyen faktörlerdir. Azot oksit ve sülfür oksit emisyonları asit yağmurlarına sebep olmakta ve ekim alanlarını etkilemektedir. Karbon monoksit ve partikül madde emisyonları ise hava kalitesini bozmakta ve insan sağlığına zarar vermektedir. Siyah karbon emisyonları ise ekim alanlarını bozmakta ve verimsizleştirmektedir.

Emisyon miktarlarının artışı dünyadaki enerji tüketimine doğrudan bağlıdır. Dünyadaki enerji tüketimi 2015 yılında 575 katrilyon Btu iken modellere göre 2030 yılında 663 katrilyon Btu ve 2040 yılında 736 katrilyon Btu olması tahmin edilmektedir. Enerjiyi tüketen çeşitli alanlar bulunmaktadır. Bunlar yapılar, ulaşım ve endüstri alanlarıdır. Yapılar, konutlar ve ticari binalardan oluşmaktadır. Endüstri alanı, üretim tesisleri, fabrikalar ve ağır sanayi bölgelerinden oluşmaktadır. Ulaşım alanı ise kara, demiryolu, hava ve deniz taşımacılığını içermektedir. Ulaşım sektörü, enerji tüketiminin önemli bir bölümünü oluşturmaktadır. 2015 yılında yaklaşık 110 katrilyon Btu enerji tüketimi sadece ulaşım sektöründe gerçekleşmiştir ve 2040 yılında 140 katrilyon Btu enerji tüketimi olması beklenmektedir. Ayrıca ulaşım sektörü dünya emisyon miktarlarında da önemli bir paya sahiptir. Avrupa Enerji Ajansı'nın verilerine göre karbon monoksit emisyonlarının %18.84'ü kara taşımacılığından, %0.11'i demiryolu taşımacılığından, %0.99'u hava taşımacılığından ve %1.94'ü deniz taşımacılığından; azot oksit emisyonlarının %28.65'i kara taşımacılığından, %0.94'ü demiryolu taşımacılığından, %6.59'u hava taşımacılığından ve %20.98'i deniz taşımacılığından; sülfür oksit emisyonlarının %7.71'i kara taşımacılığından, %0.02'si demiryolu taşımacılığından, %0.9'u hava taşımacılığından ve %11.8'i deniz taşımacılığından; partikül madde tip (PM10) emisyonlarının %0.48'i kara taşımacılığından, %0.54'ü demiryolu taşımacılığından, %0.48'i hava taşımacılığından ve %4.63'ü deniz taşımacılığından; ve partikül madde

tip (PM2.5) emisyonlarının %9.98'i kara taşımacılığından, %0.6'sı demiryolu taşımacılığından, %0.87'si hava taşımacılıktan ve %8.57'si deniz taşımacılığından oluşmaktadır.

Deniz taşımacılığı, ulaşım alanının önemli bir kısmını oluşturmaktadır. Dünya ticaretinin %90'ı, Avrupa Birliği'nin dış ticaretinin %90'ı ve iç ticaretinin %40'ı bu yolla yapılmaktadır. Deniz taşımacılığında 2012 yıllında 300 milyon ton yakıt harcanmış, 938 milyon ton karbondioksit, 19 milyon ton azot oksit, 10.2 milyon ton sülfür oksit, 1.4 milyon ton partikül ve 936 bin ton karbon monoksit emisyonu atmosfere verilmiştir. Deniz taşımacılığındaki dikkate alınması gereken bu emisyon miktarlarını azaltmak için, Uluslararası Denizcilik Örgütü çalışmalar yapmaktadır. Karbondioksit emisyonlarını azaltmaya yönelik, MARPOL Ek-VI altında Gemilerde Enerji Verimliliği Sözleşmesi yürürlüğe girmiş ve en son IMO Veri Toplama Sistemi 1 Mart 2018'de yürürlüğe girmiştir. Diğer yandan Avrupa Birliği ülkeleri tarafından MRV Regülasyon'u 1 Temmuz 2015 yılında yürürlüğe sokularak gemilerden kaynaklı karbondioksit emisyonlarının kayıt altına alınması ve azaltılmasına yönelik çalışmalar desteklenmektedir. Azot oksit emisyonlarını azaltmaya yönelik IMO NO_X Kod ile beraber Emisyon Kontrol Alanları içi ve dışı olarak makine hızını bağlı olarak sınırlar belirlenmiş ve hem makine üreticilerinin bu sınırlara uygun makine üretmesi hem de gemilerde bu sınırlara uygun makinelerin kullanılması standart haline sokulmuştur. Sülfür oksit ve partikül madde emisyonları için gemilerde kullanılacak yakıtların içeriğine sülfür sınırı getirilmiş ve hem Emisyon Kontrol Alanları içi hem de dışı olmak üzere bu sınırlar belirlenmiş ve gemilerde standarda uygun yakıtların kullanımı amaçlanmıştır.

Gün geçtikçe emisyon kuralları katılaşmaktadır. Bu kurallara uygunluk sağlanabilmesi için gemilerde, çeşitli emisyon azaltma teknolojileri ve metotları uygulanmaktadır. Bunlar, azot oksit emisyonlarını azaltmak için egzoz gazı resirkülasyon sistemi, seçici katalitik azaltma, silindir içine su verilmesi ve makine modifikasyonları iken sülfür oksit emisyonları için ise sülfür oksit filtreleme sistemi kullanılmaktadır. Ancak bu yöntemler hedefledikleri emisyon miktarlarını azaltsalar da diğer emisyonlara etkileri olmamakta diğer yandan makine verimini düşürdüklerinden karbondioksit emisyonlarında da artışı sebep olmaktadırlar. Bu yöntemlere ek olarak gemilerde alternatif yakıtların kullanılması, azot oksit, sülfür oksit, karbondioksit ve partikül madde emisyonlarını aynı anda düşürme potansiyeline sahiptir. Gemilerde kullanılabilecek alternatif yakıtlar, sıvılaştırılmış doğalgaz, sıvılaştırılmış petrol gazı, metanol, etanol, dimetil eter, biyodizel, biyogaz, sentetik yakıtlar, hidrojen, elektrik ve nükleer yakıt olarak sayılabilir. Bunlara ek olarak amonyak da son yıllarda alternatif yakıt olarak düşünülmektedir. Dünya üzerinde 116 adet sıvılaştırılmış doğalgaz kullanan gemi seyir yapmakta olup, 112 adet yeni sipariş verilmiş ve 93 adet de sıvılaştırılmış doğalgaz kullanmaya hazır gemi bulunmaktadır. 2 adet metanol kullanan gemi seyir yaparken, 6 adet kimyasal tanker siparişi verilmiştir. 12 adet sıvılaştırılmış petrol gazı kullanan gaz tankeri seyir yapmaktadır. 2 adet etan kullanan gemi seyir yaparken, 2 adet de sipariş verilmiştir. Ayrıca 2 adet hidrojen kullanan gemi de seyir yapmaktadır.

Belirtilen gemi sayıları, deniz taşımacılığının alternatif yakıtlara yöneldiğini göstermektedir. Ancak bilindiği gibi gemilerdeki geleneksel yakıtlar, gemi güvenliği açısından, 60°C'nin üstünde parlama noktasına sahiptir. Diğer yandan gemilerde kullanılmaya başlanan alternatif yakıtlar genelde daha düşük parlama noktasına sahip yakıtlardır. Bu da gemilerde alternatif yakıtları kullanmadan önce gemi üzerinde modifikasyonlar yapılıp güvenlik tedbirlerinin arttırılmasını gerektirmektedir. Bunun için IGF Kodu referans alınmaktadır. Bu kod gaz ve diğer parlama noktası düşük yakıtların gemilerde kullanılması için gerekli olan minimum standartları belirlemektedir. Bir gemide kullanılacak alternatif yakıtı belirlemeden önce çeşitli faktörler ele alınmalı, yakıt özellikleri incelenmeli, yakıtın uzun dönem kullanılıp kullanılamayacağı, olgunlaşmış bir teknolojiye sahip olup olmadığı, çevre dostu olup olmadığı, emisyonlara etkisi, uluslararası kurallara uygunluğu, ilk yatırım, işletme ve yakıt maliyetleri detaylıca araştırılmalıdır.

Hazırlanan bu tez iki ana kısımdan oluşmaktadır. İlk kısımda gemilerde kullanılacak alternatif yakıtları değerlendirmek ve seçimini kolaylaştırmak adına farklı kriterler kullanılarak bir değerlendirme modeli oluşturulmuş ve çeşitli alternatif yakıtlar değerlendirilmiştir. Tezin ikinci kısmında ise bir dizel motorda metanol yakıtı, kısmi ön karışımlı yanma konsepti kullanılarak deneysel çalışma yapılmıştır. Tezin ilk kısmının amacı, gemilerde alternatif yakıtların kullanımını etkileyecek kriterler kullanılarak bir değerlendirme modeli oluşturulması, bu metot vasıtası ile hem hangi kriterlerin alternatif yakıt seçiminde daha belirleyici olduğunun görülmesi hem de hangi alternatif yakıtların gemilerde kullanılmasının daha uygun olacağının bulunmasıdır. Tezin ikinci kısmının amacı ise ilk kısımda değerlendirilen alternatif yakıtlardan en uygun olanlarından biri ile bir dizel motor üzerinde deneysel çalışma yapılması, hem farklı yüklerde yanma olayının, makine performansının ve açığa çıkan emisyonların gözlemlenmesi hem de yakıtın yanmasına etki edecek bazı parametreleri değiştirerek, bu değişimlerin makine performansı ve emisyonlara etkilerinin gözlemlenmesidir. Sonucunda da deneysel çalışmada kullanılan alternatif yakıtın gemilerde kullanıma uygun olup olmadığı ve uluslararası denizcilik emisyon kurallarına uygunluğu incelenmiştir.

Oluşturulan değerlendirme modeli tarafından değerlendirilecek alternatif yakıtlar, amonyak, etanol, hidrojen, jet yakıtı, metanol, sıvılaştırılmış doğalgaz ve sıvılaştırılmış petrol gazıdır. Değerlendirme modeli oluşturulurken, çok kriterli karar verme yöntemlerinden biri olan analitik hiyerarşi prosesi kullanılmıştır. Değerlendirme modelinde alternatif yakıtların değerlendirileceği ana kriterler, emniyet, mevzuat, güvenilirlik, teknik, ekonomi ve ekolojidir. Ana kriterlerin yanında emniyet kriterinin altında parlama noktası, kendiliğinden tutuşma noktası, yanma limitleri, alev hızı ve maruz kalma derecesi; güvenilirlik kriterinin altında olgunluk ve yakıt ikmal imkanları; teknik kriterin altında, sistemin karmaşıklığı, gemilere uygulanabilirlik ve makine parçalarına etki; ekonomi kriterinin altında ticari etki, yatırım maliyeti, bakım maliyeti ve yakıt maliyeti bulunmaktadır. Hem ana kriterlerin hem de ana kriterlerin altındaki alt kriterlerin ağırlıkları on dört eksperin anket görüşlerine göre puanlandıktan sonra analitik hiyerarşi prosesi kullanılarak bulunmuştur. Buna göre emniyet ve ekoloji kriterleri 0.346 ağırlık puanıyla ilk sıradadır. Mevzuat kriteri 0.146 ağırlık puanı ile ikinci derecede etki etmektedir. Alternatif yakıtların her bir kriterde değerlendirilmesi ise alternatif yakıtların fiziksel ve kimyasal özelliklerinin birbirleri ile kıyaslanması, mevzuata uygunlukları, sistem gereklilikleri, yakıt ikmal noktaları, olgunluk dereceleri gibi sayısal olmayan verilerin sayısal veriye dönüştürülmesinden sonra birbirleri ile kıyaslanması şeklinde, analitik hiyerarşi prosesi kullanılarak yapılmıştır. Değerlendirme modelinin sonuçlarına göre sıvılaştırılmış doğalgaz 0.234 ağırlık puanı ile en uygun yakıt olarak çıkmıştır. İkinci sırada 0.151 ağırlık puanı ile metanol, üçüncü sırada ise 0.148 ağırlık puanı ile amonyak en uygun yakıtlardan olmuştur.

Tezin ikinci kısmında metanol ile deneysel çalışma yapılması planlanmıştır. Metanolün seçilmesinde hem bu yakıtın denizcilik sektörü açısından güncelliğinin olması hem de deneysel çalışma esnasında laboratuar emniyetinin daha kolay sağlanabilecek olması, geleneksel yakıtlara benzerliği, normal koşullarda sıvı halde depo edilebilmesi ve sülfürsüz bir yakıt olması etkili olmuştur. Metanolün dizel motorlarda yakılabilmesi için birçok yanma konsepti uygulansa da kısmi ön karışımlı yanma konsepti ile çalışma yapılmıştır. Bunun sebebi makine üzerinde daha az modifikasyon ihtiyacının olması, makinede yüksek verim elde edilmesi, düşük azot oksit ve partikül madde emisyonları, metanolün kısmi ön karışımlı yanma ile yakılmasına ilişkin literatürdeki boşluklar ve kısmi ön karışımlı yanmanın gemi ana makineleri için uygulanabilir olmasıdır.

Deneysel çalışmalar, Lund Üniversitesi'nin test laboratuarındaki Scania D13 dizel motoru üzerinde gerçekleştirilmiştir. Normalde altı silindirli olan bu motor, deneysel çalışmalar için tek silindirinde yanma gerçekleşecek şekilde modifiye edilmiştir. Testler, 2 bar, 3 bar, 5 bar, 8 bar ve 10 bar indike ortalama efektif basınç yüklerinde gerçekleştirilmiştir. 2 bar indike ortalama efektif basınç yükünde, emme havası sıcaklığının yanmaya, makine performansına ve emisyonlara etkisi incelenirken, 3 bar indike ortalama efektif basınç yükünde, yakıt püskürtme zamanının yanmaya, makine performansına ve emisyonlara etkisi incelenmiştir. 5 bar ve 8 bar indike ortalama efektif basınç yüklerinde genel yanma trendleri, makine performansı ve emisyonlar incelenmiştir. 10 bar indike ortalama efektif basınçta ise tek yakıt püskürtmesi ve ayrık yakıt püskürtmesi denenmiştir. Ayrık püskürtme esnasında yakıt püskürtme parametrelerinden, ilk püskürtme zamanının etkileri, ikinci püskürtme zamanının etkileri, ilk püskürtme süresinin oranının etkileri ve yakıt püskürtme basıncının etkileri incelenmiştir. Genel sonuçlara göre, makinede yanma stabilitesi COV $IMEP_n$ %2 ile iyi durumdadır. Makine verimi minimum 0.44 maksimum 0.49 olurken, yanma verimi minimum 0.89 iken 5 bar indike ortalama efektif basınç yükten sonra 0.99'un üzerindedir. Karbon monoksit ve yanmamış hidrokarbon emisyonları 5 bar indike ortalama efektif basınç yükten sonra 0.2 g/kWh olarak düşük seyretmiştir. Azot oksit emisyonları, 5 bar ortalama efektif basınç yüke kadar azot oksit tier III emisyon limitlerinin altındayken, 8 ve 10 bar ortalama efektif basınç yüklerinde 5 g/kWh ve 5.5 g/kWh ile tier II emisyon limitlerinde seyretmiştir.

Deneysel çalışmalar, makinenin ısınma sorunları nedeniyle 10 bar ortalama efektif basınca kadar yapılabilmiş, makinenin tam yükü olan 20 bar ortalama efektif basınç yüküne çıkılamamıştır. Bu nedenle 10 bar ile 20 bar arasındaki spesifik yakıt tüketimi, yanma verimi, makine verimi ve emisyon değerleri alınan verilere göre eğri uydurularak trendi tahmin edilmeye çalışılmıştır. Buna göre en düşük spesifik yakıt tüketimi, 381 g/kWh ile 16 bar indike ortalama efektif basınç yükünde elde edilmiştir. Yanma verimi 0.99'un üzerinde seyrederken, makine verimi 0.485 ile 16 bar indike ortalama efektif basınçta elde edilmiştir. Karbondioksit miktarı 16 bar indike ortalama efektif basınçta 524 g/kWh ile en düşük seviyesindedir. Karbon monoksit ve yanmamış hidrokarbon emisyonları 0.2 g/kWh ile 20 bar indike ortalama efektif basınç yüküne kadar devam etmiştir. Azot oksit emisyonları ise 13.5 bar indike ortalama efektif basınç yüke kadar azot oksit tier II limitleri altında seyrederken, daha yüksek yüklerde bu limiti aşmıştır. Ancak daha önce aynı test motoru üzerinde metanol ile yapılan deneylerde egzoz gaz resirkülasyon sistemi kullanıldığında azot oksit emisyonlarının rahatlıkla 0.4 g/kWh'in altına indirildiği belirtilmişti. Bu da gösteriyor ki egzoz gaz resirkülasyonu kullanıldığında, azot oksit emisyonları azot oksit tier III limitlerinin altında kalacaktır.

Bu tez çalışması göstermiştir ki oluşturulan değerlendirme modeli deniz taşımacılığının gerçekleri ile örtüşmekte ve gemilerine alternatif yakıt seçiminde bulunacak olan karar vericilere yön gösterebilmektedir. Deneysel çalışma kısmı ise metanol yakıtının kısmi ön karışımlı yanma konsepti kullanılarak bir dizel motorda iyi bir makine stabilitesi, yüksek makine verimi ve testlerin genelinde düşük emisyon miktarları ile yakılabileceğini göstermiştir. Metanol yakıtının sülfürsüz oluşu sülfür oksit emisyonlarının açığa çıkmamasını sağlarken, yine metanolün kimyasal özelliği ve kısmi ön karışımlı yanma konsepti sayesinde partikül emisyonlarının sıfıra yakın olmasını sağlamaktadır. Belli bir yüke kadar azot oksit tier III emisyon limitleri altında seyreden azot oksit emisyonları da bu seviyeyi aştığında egzoz gaz resirkülasyonu kullanılarak yine tier III limitleri altına indirilebilmekte ve regülasyonla uyum göstermektedir. Karbondioksit emisyonları için ise metanolün düşük karbon içermesi, bu emisyonların daha az atmosfere verilmesini sağlamaktadır. Eğer ileride karbon nötr olan biyo-metanol kullanımı yaygınlaşırsa karbondioksit emisyonlarının kayıtlara geçirilmesine de gerek kalmayacaktır. Metanol kısmi ön karışımlı yanma konsepti güncel karbondioksit, azot oksit ve sülfür oksit emisyon kuralları ile uyumlu olduğunu göstermiştir.

1. INTRODUCTION

Nowadays, air pollution, global warming, and climate change are important agenda topics. Emissions from the process of various industries promote global warming which is higher recently than the signed non-binding agreement at United Nations Climate Change Conference COP21 at Paris, France. According to this agreement, the increase of the world's average temperature will be limited at no more than 2°C above pre-industrial levels while it will be tried to keep the increase to 1.5°C above pre-industrial levels (EC, 2019). The global warming increases by the excess amount of greenhouse gases (GHG) that carbon dioxide (CO_2) is one of the important GHG with a high production amount. Effects of global warming worldwide such as extreme rain, flood, hurricanes, melting of the glaciers, drought, etc. are the sign of climate change. However, there is an effort to reduce global warming, the increase of the world energy consumption neutralizes these efforts. Besides global warming, air pollution is important for human health and vegetation areas. The nitrogen oxide (NO_X) emission and, sulfur oxide (SO_X) emission are the reason for acid rains. The carbon monoxide (CO) and particulate matter (PM) emission reduce the air quality, and black carbon (BC) emission degrades the vegetation areas (Janssen et al., 2012). Energy consumption has been increasing and also the emissions have been rising due to the increased energy consumption. Figure 1.1 shows world energy consumption in quadrillion Btu (EIA, 2017). The data until the year 2015 is actual while remaining years are estimated. It can be seen from the graph that the world energy consumption is 575 quadrillion Btu in 2015 and it is estimated that it will increase to 663 quadrillion Btu in 2030 and 736 quadrillions Btu in 2040.

There are various energy end-users which are building, transportation, and industry. The building part of the end-users involves residential areas and commercial buildings. The industry part of the end-users includes production facilities, factories, and heavy-industry areas. And the transportation part of the end-users includes road, railway, aviation, and shipping.

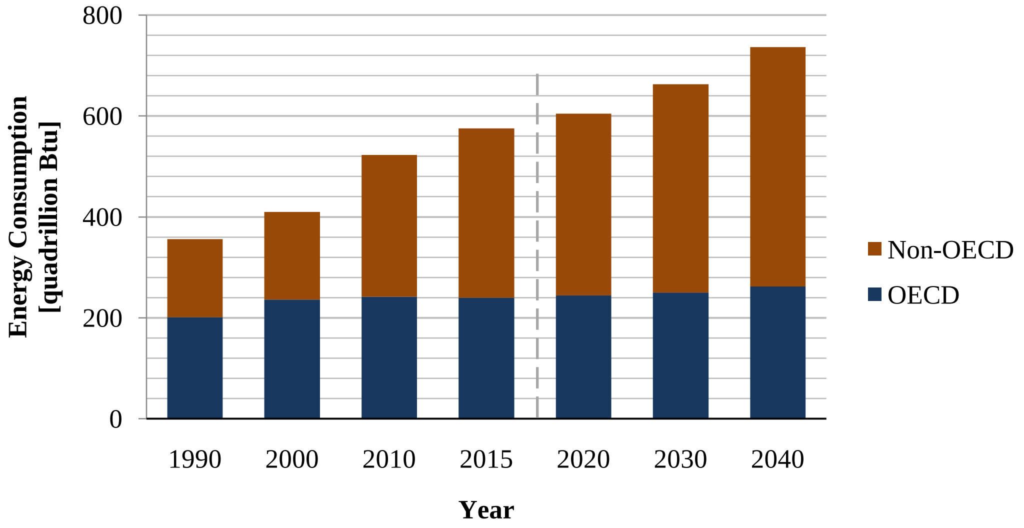

Figure 1.1 : World energy consumption in quadrillion Btu (EIA, 2017).

The transportation sector is one of the important consumers of world energy. Figure 1.2 shows the world energy consumption by end-use sector. It can be seen from the figure that the transportation sector consumed approximately 110 quadrillions Btu in 2015, and according to the predictions it will increase approximately to 140 quadrillions Btu in 2040.

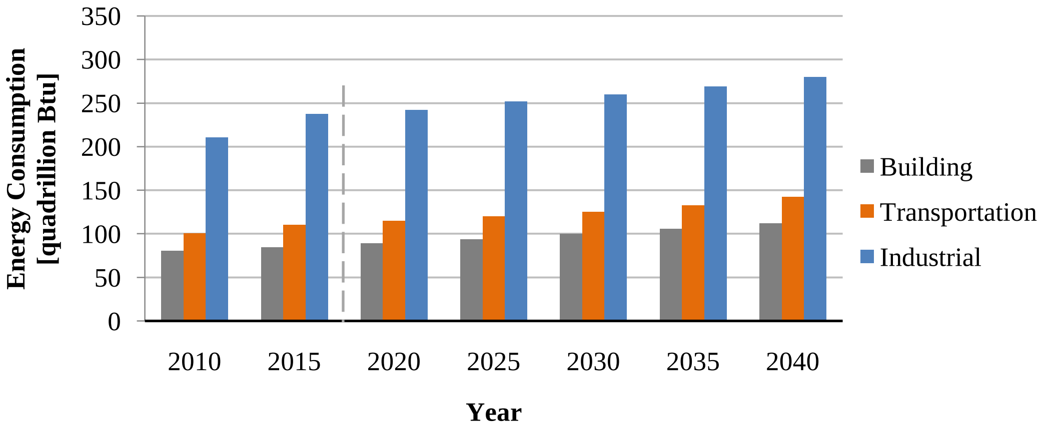

Figure 1.2 : World energy consumption by end-use sector (EIA, 2017).

The transportation sector has an important share of worldwide emissions. According to EEA (2019), road transport has a share of 18.84% at the CO emissions, 28.65% at the NO_X emissions, 0.09% at the SO_X emissions, 7.71% at the PM10, and 9.98% at the PM2.5 emissions. The railway transport has the shares of 0.11%, 0.94%, 0.02%, 0.54%, and 0.60% for the CO, NO_X, SO_X, PM10, and PM2.5 emissions, respectively. The aviation sector has the percentages of 0.99%, 6.59%, 0.90%, 0.48%, and 0.87%

for the CO, NO_X, SO_X, PM10, and PM2.5, respectively. Lastly, the shipping sector has a share of 1.94% at the CO emissions, 20.98% at the NO_X emissions, 11.80% at the SO_X emissions, 4.63% at the PM10, and 8.57% at the PM2.5 emissions.

The shipping sector is the most important transportation type and constitutes a major part of worldwide trade. It forms the 90% of the worldwide trade (Deniz and Zincir, 2016), and 90% of the outer freight and 40% of the inner freight of the European Union is done by the shipping sector (Fan et al., 2018). The shipping sector consumes 300 million tons of fuel annually while doing worldwide trade and produces 938 million tons of CO_2 emissions, 19000 thousand tons of NO_X emissions, 10240 tons of SO_X emissions, 1402 thousand tons of PM emissions, and 936 thousand tons of CO emissions in 2012 (IMO, 2014).

1.1 International Shipping Emission Rules and Regulations

The shipping emissions are in a remarkable amount and they have to be controlled and mitigated. International Maritime Organization (IMO) has been working on international rules and regulations to reduce shipping emissions. The regulated emissions are CO_2, NO_X, SO_X, and PM. This section gives information about international shipping rules and regulations.

1.1.1 CO_2 emission rules and regulations

The CO_2 emissions are related to the carbon content of the fuel combusted and it is impossible to prevent the CO_2 formation if the burned fuel involves carbon atom in its structure. However, it can be decreased by reducing consumed fuel by the main engine or auxiliary engines. Lower fuel consumption can be obtained by increasing energy efficiency on ships. The energy efficiency improvement can be done by design or retrofit measures on the hull, propeller, rudder, or on the main engine, and operational measures such as reduced ballast, hull coating, hull and propeller efficiency monitoring, speed reduction, operational energy-saving awareness, weather routing, and performance monitoring (Talay and Deniz, 2014).

IMO has regulated the CO_2 emissions by the Regulations on Energy Efficiency for Ships in MARPOL Annex VI and it was entered into force on 1 January 2013 (IMO, 2011). This regulation aims to control and mitigate CO_2 emissions from the existing and new building ships. The Energy Efficiency Design Index (EEDI) term was defined for the new building ships. It aims to increase the energy-efficient equipment and engine usage on the new building ships. Its unit is grams of CO_2 per tonne mile. There are two types of EEDI. The first one is ‘Attained EEDI’ which is the actual EEDI calculated for the specific ship. And the second one is ‘Required EEDI’ which is the allowable maximum EEDI limit for the specific ship by the regulation. Required EEDI value has reduced within the years by the phases. Table 1.1 shows the phase numbers, year intervals, and EEDI reduction amounts.

Table 1.1 : EEDI reduction phases (Bazari, 2016).

Phase	Year	Reduction
0	2013-2015	0
1	2015-2020	10%
2	2020-2025	15-20%
3	2025-	30%

The Ship Energy Efficiency Management Plan (SEEMP) was another defined term with the Energy Efficiency Regulation for the existing ships. It is a mandatory plan for the ships and it aims to increase the energy efficiency of a ship by improving the efficiency of the operations on a ship. These measures are mandatory for the Regulation. Also, there is a voluntary voyage-based calculation, which is named as Energy Efficiency Operational Indicator (EEOI), aims to reduce CO_2 emissions emitted at a voyage (Zincir and Deniz, 2016).

Another regulation for controlling and mitigating the CO_2 emissions is Monitoring Reporting Verification (MRV) Regulation entered into force by the European Union, Norway, and Iceland on 1 July 2015 (Url 1). The purpose of the regulation is to record and control the annual CO_2 emissions of ships larger than 5000 GRT calling to the EU, Norway or Iceland ports and encourage to decrease CO_2 emissions. The annual recording was started on 1 January 2018 by gathering fuel consumption data from the ships and the CO_2 emissions have been calculated by using the carbon content coefficient of the consumed fuels.

The latest regulation to mitigate the CO_2 emissions is IMO Data Collection System which entered into force on 1 March 2018 (Url 2). It is amendments to MARPOL Annex VI by the resolution MEPC.278(70). This regulation is similar to MRV Regulation. It aims to collect the annual fuel consumption data of ships larger than 5000 GRT is calling to any ports worldwide. The first reporting period was started on

1 January 2019 (Url 1). In addition to the reporting, update to the SEEMP as the SEEMP Part II that includes data collection and reporting method, was requested by the Regulation.

1.1.2 NO_X emission rules and regulations

The main source of the NO_X formation is the oxidation of the nitrogen in the charge air in the cylinder with the promotion of the high in-cylinder temperature during the combustion event. Another source can be the oxidation of nitrogen in the burned fuel (Heywood, 1988).

The NO_X Technical Code, Regulation 13 of MARPOL Annex VI limits the NO_X emissions from ships. The ships which have the engine power above 130 kW are regulated by this code. Also, the Code provides regulation-compliant engine manufacturing and engine usage on ships, and certification of the engines on ships. The NO_X Technical Code entered into force at the resolution MEPC.177(58) on 10 October 2008 (IMO, 2008). There are three tier levels also different for the engine speed limits the emitted NO_X emissions from ships (Url 3). Tier II is applied outside of Emission Control Areas (ECA) while Tier III is applied inside ECA. Table 1.2 shows the NO_X emission limits by tiers.

Table 1.2 : NO_X emission limits (Url 3).

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45.n^{(-0.2)}$	9.8
II	1 January 2011	14.4	$44.n^{(-0.23)}$	7.7
III	1 January 2016	3.4	$9.n^{(-0.2)}$	2.0

1.1.3 SO_X and PM emission rules and regulations

Regulation 14 of MARPOL Annex VI limits the fuel sulfur content mass by mass (m/m) to mitigate the SO_X and PM emission from ships (Url 4). There are different limits for inside ECAs and outside ECAs. Table 1.3 shows the SO_X and PM emission limits for inside and outside ECAs changing by years.

Designated ECAs are the Baltic Sea area and the North Sea area for the SO_X emissions only, North American area and the United States Caribbean Sea for the SO_X, NO_X, and PM emissions (Url 4). North Sea area is going to apply ECA limits for NO_X emissions from 2021 (Chryssakis et al., 2017). Additionally, there are candidates to become ECA, such as the Bosphorus Strait and Sea of Marmara, Hong Kong, and the coastline of Guangdong, China (Chryssakis et al., 2014).

Table 1.3 : SO_X and PM emission limits (Url 4).

Outside ECA SO_X and PM Limits	Inside ECA SO_X and PM Limits
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020	0.10% m/m on and after 1 January 2020

On 1 January 2020, by IMO Sulfur Cap will enter into force, the shipping sector will need to cope with stricter sulfur limits outside of ECAs. The sulfur limit will be 0.50% m/m and the ships have to comply with this global limit (IMO, 2019). Around 70000 ships will need to take measures to comply with this new limit (Chryssakis et al., 2017).

1.2 Emission Abatement Technologies and Methods

As can be seen in the previous section, the shipping emission rules and regulations are stricter day-by-day. Measures have to be taken on ships to comply with the recent regulations to navigate without any problem in worldwide. There are various emission abatement technologies and methods to mitigate the regulated emissions by IMO. However, it was mentioned in the previous study that, these measures can reduce target emission types while increasing the others (Zincir and Deniz, 2014). On the other hand, alternative fuel usage as an emission abatement measure has some promising results. This section discusses some emission abatement technologies and methods.

1.2.1 Exhaust gas recirculation (EGR)

EGR is an in-cylinder intervention system that recirculates some of the exhaust gases after cool down and cleans at a separate line and deliver into the cylinder from the intake manifold. This system reduces the oxygen concentration in the charge air and decreases the maximum in-cylinder pressure which also decreases maximum in-cylinder temperature. EGR system can reduce the NO_X emissions below down to the NO_X Tier III Limit (Kristensen, 2012).

EGR system decreases the engine efficiency, increases specific fuel consumption (SFC), CO_2 emissions and PM emissions (Zincir, 2014) during reducing the NO_X emissions. It does not have any direct effect on SO_X emissions.

1.2.2 Selective catalytic reduction (SCR)

SCR is an after-treatment system that decreases the NO_X emissions by the chemical process. SCR system uses urea to reduce NO_X emissions. The urea changes to ammonia inside the reactor and ammonia reacts with the NO_X emissions and produces nitrogen and water. This system can decrease the NO_X emissions by 80-90% (Zincir, 2014; AIRUSE, 2016). This system does not have a direct effect on SO_X emissions. It reduces engine efficiency, increases SFC, and CO_2 emissions.

1.2.3 Sulfur scrubber

The sulfur scrubber is another after-treatment system that has a reduction effect on the SO_X and PM emissions. There are wet type and dry type sulfur scrubbers. The wet type scrubbers use either seawater or freshwater with a caustic soda (NaOH) solution. The seawater or the solution reacts with the SO_X emission in the exhaust and traps the sulfur inside the scrubber. The PM emission is also reduced by the wet environment inside the scrubber. The dry type scrubber uses chemicals such as calcium hydroxide ($Ca(OH)_2$) and it holds the SO_X, CO_2 and PM emissions inside the scrubber (Zincir, 2014). Also, this system decreases engine efficiency and increases the SFC with CO_2 emissions.

1.2.4 Reduction by the water

Reduction by the water is another in-cylinder intervention system for NO_X emissions. The water can be either directly injected into the cylinder or emulsified with the fuel. It decreases the in-cylinder temperature and reduces the NO_X formation rate. It increases the SFC and PM emissions (Andreoni et al., 2008), and decreases engine efficiency. It does not have a direct effect on SO_X emissions.

1.2.5 Engine modification

Various engine modification types can increase engine efficiency, reduce the CO_2, NO_X, and PM emissions directly and reduce the SO_X emissions indirectly by decreasing the SFC. The engine modifications can be injection timing retardation, increase of injection pressure, modification of compression ratio, optimization of induction swirl, modification of injector, change in injector number, and modification of intake air system (Andreoli et al., 2008). Although, these modifications can decrease the emissions and optimum operating conditions for both low SFC and low emissions can be provided, doing modifications on a ship main engine is costly and is not practical.

1.2.6 Alternative fuels

Nowadays, the usage of alternative fuels as an emission reduction method is in demand. Shipowners and operators focus on alternative fuels to comply with the strict emission regulations. The alternative fuels for the shipping sector can be liquefied natural gas (LNG), methanol, liquefied petroleum gas (LPG), ethanol, dimethyl ether (DME), biodiesel, biogas, synthetic fuels, hydrogen (mostly as a fuel cell fuel), electricity, and nuclear fuel (Chryssakis et al., 2014; Bakhtov, 2019). In addition to these alternative fuels, ammonia has been considered as a shipping fuel, recently (Sverrisdottir, 2018).

Alternative fuelled ships in worldwide are 116 LNG-fuelled ships in operation, 112 ordered new buildings, and 93 LNG ready ship projects (DNV GL, 2017), 2 methanol-fuelled ships in operation and 6 chemical tankers in order (Dolan and Anderson, 2016; Lewenhaupt, 2017), 12 LPG- fuelled gas carriers in operation (Vizcayno, 2016), 2 ethane-fuelled ships in operation and 2 ships in order, and 2 hydrogen-fuelled inland barges in operation (Zincir and Deniz, 2018b). These ship numbers can give some clue that the shipping sector heads towards the usage of alternative fuels as an emission abatement method.

Usage of alternative fuels can reduce the different type of emissions at once. It is indicated in a report that below the NO_X Tier III Limit can be achievable with the usage of alternative fuels (McGill et al., 2013). In another study, it was declared that the NO_X emission reduction is 90%, 30-50%, and 20% by using LNG, LPG, and methanol as a fuel on ships, respectively (ClassNK, 2018). Also, the CO_2 emission reduction is 23%, 20%, and 10% with LNG, LPG, and methanol, respectively. It was also indicated that there are 90-97% SO_X emission and 90% PM emission reduction. The usage of alternative fuels has more advantages than the remaining emission abatement technologies and methods. At some points, it is essential to use two emission reduction methods at the same time on a ship to decrease different type of emissions, but the alternative fuels can reduce all regulated emissions. Especially, after treatment methods decrease engine efficiency, increase fuel consumption and CO_2 emissions. On the other hand, alternative fuels can increase engine efficiency, decrease fuel consumption and CO_2 emissions. And if the used alternative fuel has lower carbon content than the conventional fuels, it results in additional CO_2 reduction.

The flashpoint of conventional marine fuels is higher than 60°C to maintain safety on ships. On the other hand, alternative fuels usually have a lower flashpoint temperature than 60°C that results in the application of special international maritime regulation to increase the safety on board (Bakhtov, 2019). This regulation is the International Code of Safety Using Gases or Other Low-flashpoint Fuels (IGF Code) which entered into force on and after 1 January 2017. The Code aims to constitute an international standard for the shipping sector for using gas or low-flashpoint fuels (IMO, 2015). To comply with the Code, there have to be some modifications are required on the engine, in the engine room, and at the fuel storage areas. Before the selection of an alternative fuel for ships, various discussions should be made to determine, what are the effects of fuel properties on the ship safety, does the selected alternative fuel and its emissions comply with the legislation, does the selected alternative fuel is a reliable fuel for the long term, does the selected alternative fuel is technically feasible, what is the effect of costs on the alternative fuel selection, and does the selected alternative fuel is ecology friendly. It is essential to correctly assess the alternative fuels in different aspects by the ship owners and the operators during the decision-making process, and use the most suitable one at their ships.

1.3 Scope and Contribution of the Thesis Study

This thesis study consists of two parts in general. The first part of the thesis (Section 2 and 3) is about assessment model for the selection of alternative fuels for shipboard usage, and the second part of the thesis (Section 4 and 5) is about an experimental study by using methanol and partially premixed combustion concept on a heavy-duty diesel engine.

The first part of the thesis focuses on ammonia, ethanol, hydrogen, kerosene, LNG, LPG, and methanol as alternative fuels for the shipping sector, after the predetermination of fuels in the literature. The assessment model uses the analytic hierarchy process to calculate the weightings of determined alternative fuels at each criterion for the study. The determined criteria for the study are safety, legislation, reliability, technical, economy, and ecology. The assessment of the alternative fuels is done within this scope, and which alternative fuels are more suitable for the shipboard usage is determined. The contribution of the first part of the thesis are:

- Finding which criterion is more important for the shipping sector and what is the effect of criteria during the decision-making process of alternative fuel selection for ships.
- Finding which alternative fuel is more suitable for shipboard usage. What are the effects of physical and chemical properties, legislative compliance, availability, maturity, system specifications, costs, and ecological compliance on the decision-making process of alternative fuel selection for ships.

The second part of the thesis focuses on the experimental studies with the methanol partially premixed combustion concept. The experiments are conducted from low loads to medium loads of the heavy-duty diesel engine. The combustion properties, engine efficiency, and engine emissions are investigated. The contribution of the second part of the thesis are:

- Understanding the effect of intake temperature on the combustion event, engine efficiency, and engine emissions at the low load operation of the engine during the single injection strategy.
- Understanding the effect of the start of fuel injection timing on the combustion event, engine efficiency, and engine emissions at the low load operation of the engine during the single injection strategy.
- Understanding the effect of the start of fuel injection timing on the combustion event, engine efficiency, and engine emissions at the medium load operation of the engine during the single injection strategy.

- Understanding the effect of fuel injection parameters (first injection timing, second injection timing, first injection duration portion, and rail pressure) on the combustion event, engine efficiency, and engine emissions at the medium load operation of the engine during the split injection strategy.

- Investigating methanol partially premixed combustion concept on a diesel engine to understand that this fuel - combustion concept combination is usable or not for the ship engines and does the combustion products comply with the international shipping emission rules and regulations.

2. ASSESSMENT MODEL FOR SELECTION OF ALTERNATIVE FUELS FOR SHIPBOARD USAGE

In this section of the thesis, the alternative fuels which have been used at the previous studies in the literature are investigated. The alternative fuels are determined for use in the thesis. After the determination of the alternative fuels, the assessment model is formed by specifying the assessment criteria. The criteria weightings are calculated by gathering expert opinions while the alternative fuel weightings for criteria are calculated by earned points at each criterion. Lastly, the final performance point of the alternative fuels is found for the suitability of the alternative fuels for shipboard usage in Chapter 3.

2.1 Motivation of the Assessment Model Formation

Various alternative fuels have been in use in the shipping sector. However positive and negative sides of these alternative fuels should be known and compared with each other before the application process of the fuel system on a ship. A tool is needed to assess alternative fuels, shows the strong and weak side of these alternative fuels and assists decision-makers before the application process.

Analytic hierarchy process, one of the popular multi-criteria decision-making methods, can show which alternative fuel is stronger or weaker than the other at each assessment criteria by doing a pair-wise comparison. If the criteria are correctly selected and the assessment structure is constituted well, the assessment can clearly show which alternative fuel is more suitable for the shipboard usage.

2.2 Determination of Alternative Fuels

Alternative fuels which are used at the thesis study, have to be determined. For this purpose, a literature search is done from Google Scholar with the keywords, diesel engine, and alternative fuels. Many studies were made with various alternative fuels in diesel engines, but a significant study number is important.

Found alternative fuels were again searched at Google Scholar with the same keywords, and exact study numbers were found. Table 2.1 shows the study numbers of alternative fuels.

The found alternative fuel number is 36, and the total study number at Google Scholar about alternative fuel use on diesel engines is 537961. As a significant study number, 15000, which is close to 3% of total researches, is selected. As a result, the number of 14 alternative fuels is in the limit, because they are above the significant study number. However, there are 14 alternative fuels in the range of 15000 study numbers, half of these alternative fuels are used for the production of bio-diesel. These alternative fuels are waste cooking oil, palm oil, corn oil, pyrolysis oil, rapeseed oil, and soybean oil. For this reason, these fuels are not considered as alternative fuels for the ships and are not included in the thesis. Figure 2.1 shows the study numbers of determined alternative fuels for the thesis study. Hydrogen has the highest number of the study and ethanol and methanol follow hydrogen afterward. Hydrogen, ethanol, methanol, ammonia, kerosene, liquefied petroleum gas, and liquefied natural gas are evaluated by the generated assessment model for finding the suitability of the alternative fuels for shipboard usage.

Table 2.1 : Study numbers on diesel engine with alternative fuels (GS, 2017)

Alternative Fuels	Search Result	Alternative Fuels	Search Result
Hydrogen	78400	Ethane	11600
Ethanol	47200	Fischer-Tropsch Fuel	11400
Methanol	43300	Olive Oil	10100
Waste Cooking Oil	32700	Coconut Oil	9410
Palm Oil	28200	Iso-octane	9110
Corn Oil	27300	Cottonseed Oil	7700
Ammonia	24700	Peanut Oil	7290
Pyrolysis Oil	22600	Pentane	7090
Kerosene	22000	Propanol	6040
Rapeseed Oil	20600	Linseed Oil	5800
Soybean Oil	20500	Dodecane	5210
LPG	19600	Hexadecane	4870
LNG	19500	Mahua Oil	2990
Jatropha Oil	16000	Sesame Oil	2560
Dimethyl Ether	14700	Hazelnut Oil	1300
Sunflower Oil	14400	Pentanol	1180
Butanol	12300	Croton Oil	1030
Shale Oil	11800	Nitromethane	781

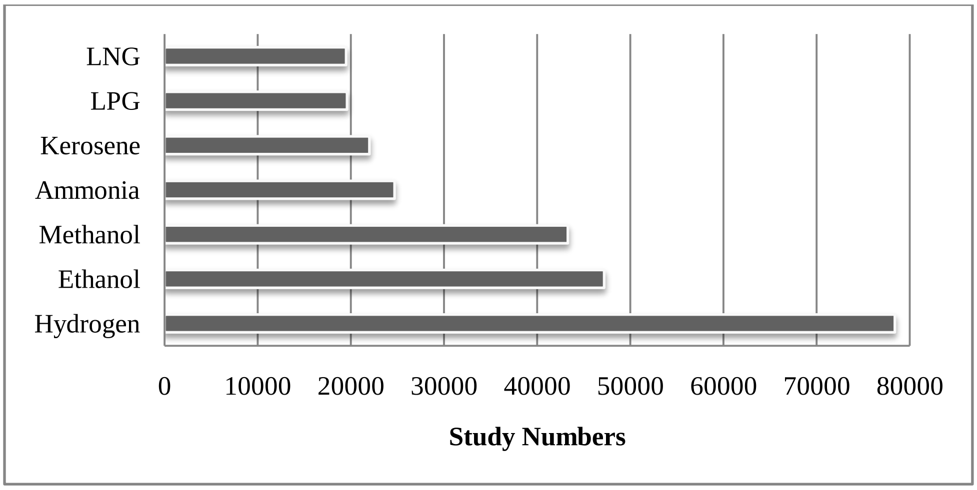

Figure 2.1 : Study numbers of determined alternative fuels for the thesis study.

2.3 Specifications of Alternative Fuels

In this section, specifications of ammonia, ethanol, hydrogen, kerosene, LNG, LPG, and methanol are mentioned and showed in Table 2.2.

2.3.1 Ammonia

Ammonia is a hydrogen carrier and carbon-free fuel which does not emit CO_2 as a combustion product (Reiter and Kong, 2011). Besides its characteristic of carbon-free structure, it has a high octane number. Ammonia is produced by various fossil fuels, such as coal, natural gas, petroleum, etc. or renewable energy sources (Zamfirescu and Dincer, 2009). Storage of ammonia is provided by moderate pressure at ambient temperatures, in the storage tanks without the tank materials of copper, nickel, and plastics (Reiter and Kong, 2010). Its renewability and carbon-free structure lead researchers to do the study with ammonia on diesel engines (Reiter and Kong, 2010; Reiter and Kong, 2011, Gill et al., 2012).

2.3.2 Ethanol

Ethanol is volatile and colorless alcohol with a slight odor. It can be manufactured from sugarcane, waste biomass materials, corn, barley, sugar beets, food and wood wastes. In addition to these resources, it can be produced from ethane or ethylene by chemical reactions (Parthasarathi et al., 2014).

Due to its renewability, ethanol is one of the alternative fuels paid attention by the researchers (Sarjovaara et al., 2013; Parthasarathi et al., 2014; Britto Jr and Martins, 2014). Ethanol can be stored solely in room conditions, or emulsified with diesel fuel with the aid of additives. In this study, it is assumed that ethanol is stored solely.

2.3.3 Hydrogen

Hydrogen is non-toxic, odorless, and renewable energy carrier. The combustion product of hydrogen is water, for this reason, researchers have been paid attention to it as an alternative fuel (Yang et al., 2015; Jhang et al., 2016; Karagöz et al., 2016). It is found that hydrogen has the highest amount of research numbers in the literature. Hydrogen has a wide flammability range, high flame speed, high diffusivity, zero carbon and sulfur content (Deniz and Zincir, 2016). The only drawback of the combustion process is its high auto-ignition temperature of 585 ºC. Hydrogen can be stored as compressed or liquefied conditions at -253 ºC (Deniz and Zincir, 2016). In this study, it is assumed that hydrogen is stored in a compressed condition.

2.3.4 Kerosene

Kerosene is produced from petroleum, and it is one of the significant fuels for transportation. It is mostly used as aviation fuel. In addition to the aviation industry, it can be used at diesel engines. North Atlantic Treaty Organization (NATO) is aimed to use JP-8, a type of kerosene, for their automobiles and equipment (Tay et al., 2016). Kerosene can be blended with diesel fuel to improve the cold flow characteristics of diesel fuel (Patil and Thipse, 2014). There are many types of research about the use of kerosene fuel at diesel fuels (Kadhim, 2015; Tay et al., 2016; Solmaz et al., 2016).

2.3.5 Liquefied natural gas

Liquefied natural gas (LNG) is the cooled state of natural gas at -162 ºC (Elgohary et al., 2014). Natural gas is a mixture of methane, ethane, propane, and butane. It is one of the attractive alternative fuels nowadays, due to its low-sulfur or sulfur-free content, and lower CO_2 emission. There are many studies in the literature about using LNG on diesel engines (Papagiannakis et al., 2010; Cheenkachorn et al., 2013; Mansor, 2014)

2.3.6 Liquefied petroleum gas

Liquefied petroleum gas (LPG) is a mature alternative fuel for passenger cars for many years. It is produced by the separation of denser hydrocarbons from natural gas at the petroleum refinery (Kjartansson, 2011). LPG consists of propane, propylene, butane and some other light hydrocarbons (Ashok et al., 2015). LPG can be liquefied under low pressure and atmospheric temperature. Because LPG is mature, there have been many kinds of research done in the literature (Kumaraswamy and Prasad, 2012; Nutu et al., 2014; Chakraborty et al., 2016).

2.3.7 Methanol

Methanol is another alcohol type. Over 70 million tons of methanol are produced annually (Andersson and Salazar, 2015). Methanol is produced mainly from natural gas, but it can be also produced from renewable feedstock like municipal waste, industrial waste, biomass, and carbon dioxide (DNV GL, 2016). Methanol can be stored in regular tanks with small modifications at ambient temperatures the same as ethanol. Methanol has been taken attention by researchers in various industries and has many studies about methanol use on diesel engines (Zhang et al., 2013a; Geng et al., 2014; Svensson et al., 2016).

Table 2.2 : Specifications of the alternative fuels.

	Ammonia	Ethanol	Hydrogen	Kerosene	LNG	LPG	Methanol
Flashpoint (°C)	132	13	-150	38	-188	-105	12
Auto-ignition (°C)	650	363	585	210	537	450	464
Density (kg/m^3)	682	794	83.8	775	450	540	798
Lower Heating Value (MJ/kg)	18.8	27	119.9	43.5	46	46.3	19.9
Flammability (%)	15-25	3.3-19	4-75	0.7-7	5-15	2-10	6-36.5
Flame Speed (cm/s)	14	41	270	60	38	40	50
References	Reiter and Kong, 2011; Nozari and Karabeyoglu, 2014; Url 5; Url 6	Labeckas et al., 2014; Parthasarathi et al., 2014; Deniz and Zincir, 2016; Url 7	Jhang et al., 2016; Deniz and Zincir, 2016; Url 5	Aydin et al., 2010; Wu, 2016; Url 8; Url 9	Deniz and Zincir, 2016; Url 11	Liao, et al., 2005; Nutu et al., 2014; Url 10; Url 12	Deniz and Zincir, 2016; Url 13

2.4 Assessment Model Tool

Multi-criteria decision making (MCDM) methods are important tools for giving decisions, evaluating the performance, selecting an item, etc. There are various MCDM methods which are multi-attribute utility theory, analytic hierarchy process (AHP), fuzzy set theory, case-based reasoning, data envelopment analysis, simple multi-attribute rating technique, goal programming, ELECTRE, PROMETHEE, simple additive weighting, technique for order of preference by similarity to ideal solution, and combination of these methods. AHP is one of the popular MCDM methods which has many advantages, easy to use, pair-wise comparison of the alternatives and criteria, not data-intensive, and can easily be used in various problems (Velasquez and Hester, 2013).

In the thesis study, assessment is done by the assist of AHP which was found by Saathy (Saathy, 1980). AHP is a powerful decision-making tool for complex, multi-criteria problems. It is useful if data are both quantitative and qualitative or criteria weights are given referred to expert opinions (Winebrake and Creswick, 2003). It can easily adapt to a performance-type decision-making process (Velasquez and Hester, 2013), which is the main issue in this study. Table 2.3 shows the steps of the AHP method application to the decision-making problem.

Table 2.3 : Analythic Hierarchy Process application steps (Kunz, 2010).

AHP Steps
Step 1: Develop the weightings for the criterion
✓ Form a single pair-wise comparison matrix
✓ Multiply the values in each row and calculate the n th roots of each row
✓ Normalize the n th roots of each row and get the weightings
✓ Check the consistency ratio (CR)
Step 2: Develop the weightings for the alternatives
✓ Form a single pair-wise comparison matrix
✓ Multiply the values in each row and calculate the n th roots of each row
✓ Normalize the n th roots of each row and get the weightings
✓ Check the consistency ratio (CR)
Step 3: Calculation of the decision by the weighted average rating

To form a single pair-wise comparison matrix for step 1, the scale of relative importance is used to determine which item is more important than others. Table 2.4 shows the scale of relative importance.

Table 2.4 : Scale of relative importance (Ren and Sovacool, 2015).

Scales	Definition	Note
1	Equal importance	i is equally important to j
3	Moderate importance	i is moderately important to j
5	Essential importance	i is essentially important to j
7	Very strong importance	i is very strongly important to j
9	Absolute importance	i is very absolutely important to j
2, 4, 6, 8	Intermediate value	The relative importance of i to j is between to adjacent judgment

To calculate the consistency of the AHP table, equation (2.1), (2.2), and (2.3) are used (Render and Stair, 1999). W_i is weighting of i type of criterion or alternative. a_i is the sum of the row of i type of criterion or alternative. CI is the consistency index, RI is the random index, and CR is the consistency ratio. RI was developed by Saathy (Saathy, 2008), and his random index table (Table 2.5) is used while doing CR calculation.

$$\boldsymbol{\lambda_{max} = \sum_{i=1}^{n}(W_i \cdot \sum_{i=1}^{n} a_i)} \tag{2.1}$$

$$\mathbf{CI = \frac{\lambda_{max} - n}{n-1}} \tag{2.2}$$

$$\mathbf{CR = \frac{CI}{RI}} \tag{2.3}$$

Table 2.5 : Random index values (Saathy and Tran, 2017).

Order	2	3	4	5	6	7	8	9	10	11	12	13	14
Random Index (RI)	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58

2.4.1 Literature review about the assessment studies and assessment criteria

Tzeng et al. (2005), had a study to determine the best alternative fuel mode for the buses in Taiwan. They used AHP to find the weights of criteria. The criteria of the study were energy supply, energy efficiency, air pollution, noise pollution, industrial relationship, costs of implementation, costs of maintenance, vehicle capability, road facility, speed of traffic flow, and sense of comfort. The alternative fuel modes for the study were accumulated under the conventional diesel engine, alternative fuel mode, electric vehicle, and hybrid electric vehicle. The result of the assessment was the hybrid electric bus is the most suitable alternative fuel mode.

A study assessed biofuels for the utilization of these fuels to the European transport sector in 2010 and the future (Papalexandrou et al., 2008). The AHP method was used to assess biofuels. The assessment criteria were economic, potential, environmental, and resource.

Tsita and Pilavachi (2012) focused on alternative fuels for the Greek road transportation sector in their study. They assessed seven alternative fuels which were used on internal combustion engine (ICE), ICE with 1st generation biofuels, ICE with 2nd generation biofuels, hydrogen fuel cells, hybrid vehicle, plug-in hybrid vehicle, and electric vehicle. The assessment criteria were cost main criteria with the sub-criteria of implementation cost, technology maturity cost, and cost of energy and policy main criteria with the sub-criteria of CO_2 emissions, energy security, employment, and social welfare. According to their AHP result, they found that ICE blended with 1st and 2nd generation biofuels were the most suitable alternative fuels.

A study indicates that to assess the alternative marine fuels, various criteria are needed for the cost evaluation (McGill et al., 2013). These main criteria can be engine and fuel system costs with the sub-criteria of new vessel on-cost, and retrofit investments, increased maintenance cost, projected fuel cost with the sub-criteria of projected fuel price per megajoule, availability and cost of infrastructure, long-term world supply, and fuel consumption penalty, emission abatement cost with the sub-criteria of PM port compliance, SO_X ECA, NO_X ECA, and CO_2 EEDI, safety-related cost with the sub-criteria of approvals, additional insurance cost, crew training and education, and lastly, indirect cost with the sub-criteria of reduced range between bunkering, reduced cargo capacity, and increased waiting time in ports.

Another study was focused on four fuels of LNG, liquefied biogas (LBG), methanol, and bio-methanol (Brynolf et al., 2014). The purpose of the study was to compare the life cycle environmental performance of these marine fuels. They used technical aspects, economic aspects, and environmental aspects as comparison criteria in their study.

Brynolf (2014) had another study with heavy fuel oil (HFO), marine gas oil (MGO), synthetic diesel (GTL), rapeseed methyl ester (RME), synthetic biodiesel (BTL), LNG, LBG, and methanol. A detailed assessment was made with the main criteria and their sub-criteria. Technical criteria involved fuel properties, maintenance demand, fuel-pretreatment requirements, and engine adaptation as sub-criteria. Economic criteria involved investment cost, fuel price, and operational cost as sub-criteria. Environmental criteria had consequences of fuel spills and accidents, exhaust emissions, and life cycle environmental performance as sub-criteria. Finally, the last main criteria, other, had ethics, security, political and strategy aspects, public opinion, safety and safe handling criteria, and logistical criteria as sub-criteria.

Elgohary et al. (2014) evaluated coal, biodiesel, Fischer-Tropsch diesel, alcohol, hydrogen, and LNG as the possible alternative fuels for marine propulsion in the near term. They used availability, renewability, safety, cost, adaptability, performance, and environmental impact as the assessment criteria. They found that LNG can be a future marine fuel.

A previous study by Deniz and Zincir (2016) aimed to compare the alternative marine fuels for using on ships. Methanol, ethanol, LNG, and hydrogen were compared by use the AHP method. The assessment criteria were safety, global availability, bunker capability, durability, adaptability to existing ships, the effect on engine performance, the effect on engine emissions, comply with the emission regulations, effect on engine combustion chamber components, commercial effects, and costs. The safety main criteria had sub-criteria of density, auto-ignition temperature, flammability limits, stoichiometric air-fuel ratio, octane number (ON), and cetane number (CN). The durability main criteria had sub-criteria of fuel reserves, global availability, bunker capability, and trends in the future. The effect on engine emissions considered CO_2, NO_X, SO_X, PM, CO, and THC emissions, and the costs main criteria had investment costs and operational costs sub-criteria.

In another study, alternative marine fuels were assessed by using AHP (Månsson, 2017). The alternative fuels included in the study were LNG, methanol from natural gas, bio-methanol, and hydrogen from electrolysis. The assessment main criteria were economic with the sub-criteria of fuel price, operational cost, investment cost for propulsion, technical with the sub-criteria of available infrastructure, reliable supply of fuel, environmental with the sub-criteria of acidification, climate change, health impact, and social with the sub-criteria of safety and upcoming legislation. The results showed that the hydrogen from electrolysis got the highest point.

Another study was made to assess LNG, hydrotreated vegetable oil (HVO), and diesel oil as freight transport fuel in Spain (Osorio-Tejada et al., 2017). Firstly, they investigated the assessment criteria used in the previous AHP-based studies. They found that technical/operational, economic, environmental, social, and safety were the most common criteria for the assessment studies. And then, they used the economic, environmental, and social criteria in their study. They used sub-criteria of reliability, investment and operational costs, and legislation at the economic main criteria, GHG emissions, air pollutants (NO_X and PM), and noise at the environment main criteria, and employment, social benefits, and social acceptability at the social main criteria.

Oztaysi et al. (2017) made a study on alternative fuel selection for a utility company. They used biodiesel, electricity, ethanol, hydrogen, natural gas, and propane as the alternative fuel options. The assessment criteria were purchase cost and operation cost under the cost main criteria, safety, perceived quality, and performance under safety and performance main criteria, filling station availability, filling time, and driving range under the fueling convenience main criteria, GHG emission and social welfare impact under environmental and social main criteria, market penetration and secondary market development under market maturity main criteria. They found that the best alternative fuel was natural gas.

Ren and Liang (2017) had a study aimed at the sustainability assessment of alternative marine fuels. They focused on methanol, LNG, and hydrogen as alternative marine fuels. The study had the main criteria of environmental with effect on CO_2 emission, effect on NO_X emission, effect on SO_x emission, and effect on PM emission sub-criteria, the main criteria of economic with capital expenditure and operational expenses sub-criteria, the main criteria of technological with maturity, reliability, and capacity sub-criteria, and the main criteria of social with comply with emission regulations and social acceptance sub-criteria.

Sehatpour et al. (2017) made a study to find suitable alternative fuel for light-duty vehicles in Iran. They assessed compressed natural gas, liquefied petroleum gas, petroleum diesel, biodiesel, biogas, ethanol mixture (E85), methanol mixture (M85), and hydrogen.

The sub-criteria were production and distribution cost and implementation cost under economic main criteria, infrastructure availability, energy content, safety, social criteria, and social acceptance under technical main criteria, CO_2 emissions, energy security, and fuel smuggling under policy main criteria. The assessment result showed that compressed natural gas and liquefied petroleum gas were the most suitable alternative fuels.

Hansson et al. (2019) had a study that assesses seven alternative fuels for the shipping sector in 2030. These fuels were LNG, LBG, methanol from natural gas, renewable methanol, two types of hydrogen fuels for fuel cells, and HFO as a benchmark fuel. They used economic main criteria with investment cost, operational cost, and fuel price sub-criteria, technical main criteria with available infrastructure and reliable supply of fuel, environmental main criteria with acidification, health impact, and climate change sub-criterion, and social main criteria with safety and upcoming legislation sub-criteria.

2.4.2 Determination of the assessment criteria and the criteria weightings

The assessment of the alternative fuels can be made by considering various aspects related to ships, alternative fuel system or the properties of the alternative fuels. The assessment criteria in this study are determined by the examination of the previous studies in the literature and focus on the general perspective of these studies.

Under the light of the previous studies, assessment model criterions are safety, legislation, reliability, technical, economy and ecology in the thesis study. Figure 2.2 shows the assessment model scheme for evaluating alternative fuels for onboard use. It can be seen from the scheme that the safety main criterion has the sub-criterion of flashpoint, auto-ignition, flammability limits, flame speed, and exposure rate. The legislation includes all international maritime rules and regulations which are indicated in Figure 2.2, but the evaluation will be done according to the total performance point of each alternative fuel. The reliability has sub-criterion of maturity and bunkering capability, while the technical criterion has the sub-criterion of system complexity, adaptability to ships, and effect on engine components. The economy criterion has the sub-criterion of commercial effect and system costs which was constituted by investment cost, maintenance cost, and fuel cost.

The ecology performance of the alternative fuels will be evaluated according to the total performance point of each alternative fuel at the indicated items under the ecology section.

The scale of the relative importance of each alternative at each sub-criterion determined by firstly get the difference between the best alternative and the worst alternative for a criterion. The best and worst alternative is found according to their value or effect, which is gathered from the literature, on an evaluation criterion. After that difference value between the best and the worst divided to nine to form a scale of relative importance from 1 to 9 (Table 2.4). For the comparison of alternatives always bigger value be subtracted from lower value, and scale of relative importance between these alternatives is found and written to the matrix. Last thing is to calculate weightings, and CR of the matrix (Deniz and Zincir, 2016). Equation (2.4) and (2.5) are used for determining the intervals for the pair-wise comparison.

$$\mathbf{V_{dif} = V_b - V_w} \tag{2.4}$$

$$\mathbf{V_{int} = \frac{V_{dif}}{9}} \tag{2.5}$$

where V_b is the best alternative value, V_w is the worst alternative value, V_{dif} is the highest difference value between the alternatives, and V_{int} is the interval value of the pair-wise comparison.

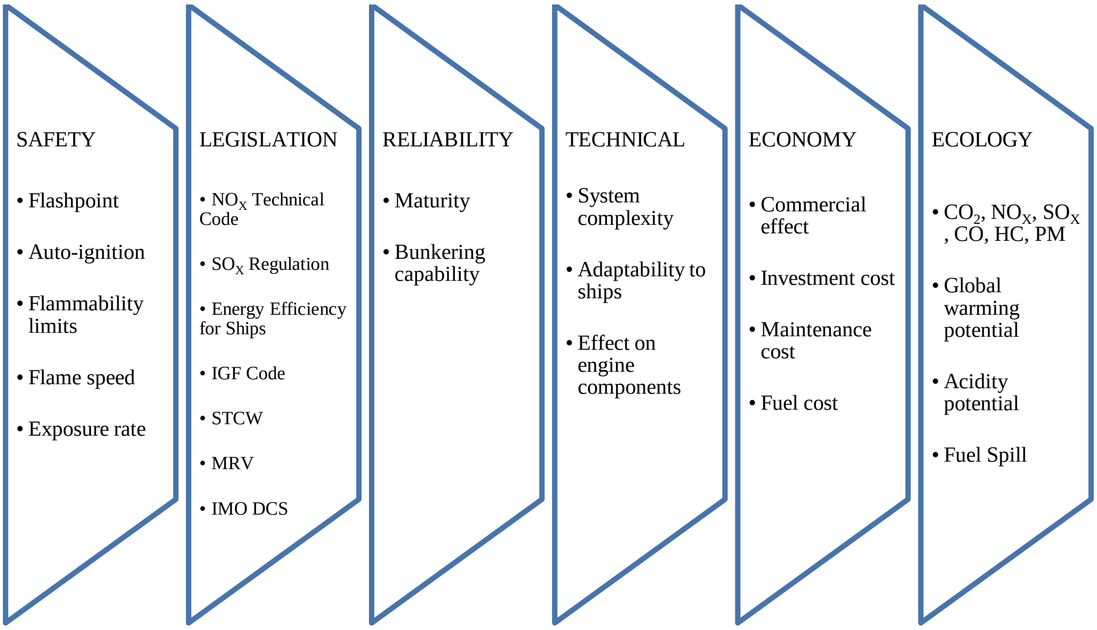

Figure 2.2 : Assessment model scheme.

2.4.3 Explanation of the main criteria and sub-criteria

The main criteria of the assessment model are safety, economy, legislation, reliability, technical, and ecology.

2.4.3.1 Safety

The safety criterion aims to evaluate alternative fuels by considering their physical properties which can affect fuel operations on a ship. These physical properties of the alternative fuels are flashpoint, auto-ignition temperature, flammability limits, flame speed, and exposure rate.

Flashpoint sub-criterion is the lowest temperature which vapor of the material will ignite by the support of an ignition source. Flashpoint of fuel is important at storage and handling because lower flashpoint temperature means more dangerous fuel. The intention of fuel to ignite by outside sources such as sparks, arc, etc. is higher if flashpoint temperature is lower.

The auto-ignition temperature sub-criterion is a limit in which a material will ignite without the support of an ignition source. If the auto-ignition temperature of the fuel is high, it's resistance to spontaneous ignition is higher. It means it is easier to store and handle these kinds of fuels in the tanks.

Combustible materials can be burned within the lower and upper fuel limits which are determined experimentally. These limits are referred to as flammability limits or explosive limits. There is a lower explosive limit which is the lowest limit of fuel concentration in the combustible mixture to be burned, and the upper explosive limit which is the highest limit of fuel concentration in the combustible mixture to be burn. If the flammability limit of fuel is wide, it means it can be burned at more variety of proportion of mixture, and it needs more precautions at storage and handling operations.

Flame speed sub-criterion is the rate of spreading of the flame at the combustion process. If the flame speed is high, it is more difficult to extinguish the flames, and it spreads quickly. Flame speed is another important factor in storage and handling operations.

Exposure limit sub-criterion is the highest permissible limit to airborne concentrations of chemical substances in which workers are exposed daily.

Threshold Exposure Limit Values (TLV) are taken into consideration in this safety evaluation model. These values are developed as guidelines to assist to prevent health hazards at workplaces, and they are not legal standards (Url 14). Table 2.6 shows the exposure limits of alternative fuels.

Table 2.6 : Allowable exposure rates of alternative fuels.

Alternative Fuels	Exposure Limit (mg/m^3 – 8h)	References
Ammonia	17	Url 6
Ethanol	1900	Url 7
Hydrogen	336	NRC, 2008
Kerosene	200	Wu, 2016; Url 15
LNG	650	Url 11
LPG	1900	Url 12
Methanol	196	Url 13

2.4.3.2 Legislation

Legislation evaluation of alternative fuels includes conformity of alternative fuels on NO_X Technical Code, SO_X Regulation, Energy Efficiency for Ships Regulation, International Code of Safety for Ships Using Gases or Other Low Flashpoint Fuels (IGF Code), Standards of Training Certification and Watchkeeping (STCW), Monitoring Reporting and Verification (MRV) Regulation, and IMO Data Collection System (DCS). Table 2.7 shows the conformity of alternative fuels on maritime regulations.

Table 2.7 : Conformity of alternative fuels on maritime regulations.

	IMO Regulations						EU
Alternative Fuels	NO_X Technical Code	SO_X Regulation	Energy Efficiency	IGF Code	STCW	IMO DCS	MRV
Ammonia	Tier II	+	+	Conventional	Usual + Toxic	+	+
Ethanol	Tier II	+	+	+	+	+	+
Hydrogen	Tier II	+	+	+	+	+	+
Kerosene	Tier II	+	-	Conventional	Usual	-	-
LNG	Tier III	+	+	+	+	+	+
LPG	Tier II	+	-	+	+	-	-
Methanol	Tier II	+	+	+	+	+	+

Regulation points are given to the alternative fuels according to their conformity with the regulations. Table 2.8 shows the regulation points. By using regulation points, alternative fuels can be compared on the AHP matrix. The regulation points in Table 2.8 are determined by the assist of emissions weight points in the previous study

(Deniz and Zincir, 2016) which will also be used in this study at Section “2.4.3.6 Ecology”. The CO_2 emission-related regulations, Energy Efficiency, IMO DCS, and MRV, get 15 points by the multiplication of the point for CO_2 emission in Table 2.28 by three. The NO_X Technical Code Tier III gets 12 points as the highest point, again using the multiplication of the NO_X emission point and three. Tier II and Tier I get 8 and 4 points, respectively. The SO_X Regulation gets 12 points by the multiplication of the SO_X emission point, 4, and three. IGF Code gets 1 if a special application is needed and gets 2 if a conventional application is needed. STCW gets 1, if the special training is needed, gets 3, if usual and toxic training is needed, and gets 5, if only usual training is adequate.

Table 2.8 : Regulation points.

Regulations		Regulation Points
Energy Efficiency		15
NO_X Technical Code	Tier I	4
	Tier II	8
	Tier III	12
SO_X Regulation		12
IGF Code	Special	1
	Conventional	2
STCW	Special	1
	Usual + Toxic	3
	Usual	5
IMO DCS		15
MRV		15

According to the conformities of the alternative fuels in Table 2.7 and regulation points in Table 2.8, the legislation points of the alternative fuels are calculated in Table 2.9. It can be seen that LNG has the highest legislation point of 71. Ammonia follows it with 70, and methanol follows with 69.

Table 2.9 : Legislation points of alternative fuels.

	IMO Regulations						EU	
Alternative Fuels	NO_X Technical Code	SO_X Regulation	Energy Efficiency	IGF Code	STCW	IMO DCS	MRV	Legislation Point
Ammonia	8	12	15	2	3	15	15	70
Ethanol	8	12	15	1	1	15	15	67
Hydrogen	8	12	15	1	1	15	15	67
Kerosene	8	12	0	2	5	0	0	27
LNG	12	12	15	1	1	15	15	71
LPG	8	12	0	1	1	0	0	22
Methanol	10	12	15	1	1	15	15	69

2.4.3.3 Reliability

Reliability evaluation is constituted by maturity and bunkering capability sub-criteria. Maturity is the stage of the technology of alternative fuels. Bunkering capability is the possible area for the supply of the ship with these alternative fuels.

The maturity of the alternative fuels is calculated according to maturity points. Table 2.10 shows the maturity points according to the maturity levels, and Table 2.11 shows the maturity points of alternative fuels.

Table 2.10 : Maturity level and points.

Maturity Level	Maturity Point
Laboratory based	1
Prototype	2
Commercial in a long period	3
Commercial in a short period	4
Commercial	5

Table 2.11 : Maturity points of the alternative fuels.

Alternative Fuels	Maturity Point
LNG	5
LPG	4
Methanol	4
Ethanol	3
Hydrogen	3
Kerosene	3
Ammonia	2

Bunkering areas of alternative fuels are shown in Table 2.12. There are thirteen regions for this study.

Table 2.12 : Bunkering areas of alternative fuels.

	Bunkering Areas												
Alternative Fuels	N. America	S. America	Baltic Region	Europe	Mediterranean	Black Sea	W. Africa	S. Africa	E. Africa	Arabian Sea	S. China Sea	E. China Sea	Oceania
Ammonia	+	+	-	-	+	+	-	-	-	+	+	-	+
Ethanol	+	+	-	+	-	-	-	-	-	+	+	+	-
Hydrogen	+	-	+	+	+	-	-	-	-	-	+	+	-
Kerosene	+	-	+	+	+	-	+	+	+	+	+	+	+
LNG	+	+	+	+	+	-	-	-	-	+	+	+	+
LPG	+	-	+	+	+	+	-	-	-	+	+	+	+
Methanol	+	+	+	+	+	+	+	+	+	+	+	+	+
References	Fraile et al., 2015; RFA, 2016; Dolan, 2017; Valladares, 2017; Url 16, Url 17, Url 18, Url 19												

2.4.3.4 Technical

The technical evaluation section assesses alternative fuels on three bases, which are system complexity, adaptability to ships, and effect on engine components sub-criteria.

System complexity is an important basis for the onboard application of alternative fuels. A more complex system means more system components, and more failure area and probability. A low number of the crew member and limited spare parts in the middle of the ocean decrease intervention to larger complex systems.

Adaptability to ships is another important issue for onboard applications. Space can be allocated for alternative fuel supply and delivery systems at new building ships, but there is not an opportunity to do this at existing ships. For this reason, the compact structure of alternative fuel supply and delivery systems is prefered.

The effect on engine components is another evaluation sub-criterion for this section. Wear, tear, choking or any other damage to engine components is important on ships, again due to lack of manpower and spare parts.

The first evaluation sub-criterion is system complexity. This study includes tank, pumps, electronic control unit (ECU), other elements, and fuel delivery type to the engine as comparison items at this sub-criterion. Each alternative fuel has different tank types, pump need, ECU function, a different type of side elements, and fuel delivery type to the engine. Table 2.13 shows these specifications of each alternative fuel.

To evaluate alternative fuels, evaluation points are given according to their complexity level. Table 2.14 shows scale points for each level of complexity. It can be seen that low complexity gets 3 points, while moderate and high get 2 and 1, respectively. Table 2.15 shows the complexity evaluation points of each alternative fuels with total complexity points. At the table, high total complexity points mean lesser complexity of the system, and low total complexity points mean higher complexity.

Table 2.13 : System components of alternative fuels.

System Components						
Alternative Fuels	Tank	Pumps	ECU	Other Elements	Delivery Type to the Engine	References
Ammonia	Storage tank	Tank to GVU / GVU to the engine	Pressure, temperature sensors, valve controllers, ventilation and leakage monitoring	Gas valve train, gas supply system, gas injection block on cylinder cover, ventilation system	Direct delivery by special GI injectors	Reiter and Kong, 2007; Reiter, 2009; Veltman and Kong, 2009
Ethanol	Storage tank	Tank to GVU / GVU to the engine	Pressure, temperature sensors, valve controllers	Fuel valve train (GVU), liquid gas injection (LGI) block on cylinder cover	Direct delivery by special LGI injectors	MAN, 2014
Hydrogen	Storage tank	Tank to GVU / GVU to the engine	Pressure, temperature sensors, valve controllers, ventilation and leakage monitoring	Gas valve train, gas supply system, gas injection block on cylinder cover, ventilation system	Direct delivery by special GI injectors	Zincir and Deniz, 2014
Kerosene	Storage tank	Transfer pump, high pressure injection	Pressure, temperature sensors, valve controllers	Primary fuel filter (water separator), secondary fuel filter	Direct delivery by injectors	Url 20
LNG	Storage tank	Tank to GVU / GVU to the engine	Pressure, temperature sensors, valve controllers, ventilation and leakage monitoring	Gas valve train, gas supply system, gas injection block on cylinder cover, ventilation system	Direct delivery by special GI injectors	Levander, 2011; HEC, 2013; MAN, 2012; Laursen, 2015
LPG	Storage tank	Tank to GVU / GVU to the engine	Pressure, temperature sensors, valve controllers, ventilation and leakage monitoring	Gas valve train, gas supply system, gas injection block on cylinder cover, ventilation system	Direct delivery by special GI injectors	Kjartansson, 2011; Laursen, 2015
Methanol	Storage tank	Tank to GVU / GVU to the engine	Pressure, temperature sensors, valve controllers	Fuel valve train (GVU), liquid gas injection (LGI) block on cylinder cover	Direct delivery by special LGI injectors	Levander, 2011; MAN, 2014; Andersson and Salazar, 2015; DNV GL, 2016;

Table 2.14 : Complexity evaluation point scale.

Complexity Level	Complexity Point
Low	3
Moderate	2
High	1

Table 2.15 : Complexity evaluation points of alternative fuels.

System Components	Ammonia	Ethanol	Hydrogen	Kerosene	LNG	LPG	Methanol
Tank	1	2	1	1	1	1	2
Pumps	1	1	1	1	1	1	1
Piping	1	1	1	3	1	1	1
ECU	1	3	1	3	1	1	3
Other Elements	1	1	1	2	1	1	1
Delivery type to the engine	1	1	1	2	1	1	1
Total Point	6	9	6	12	6	6	9

The second evaluation sub-criterion is adaptability to ships. This sub-criterion includes space need and modification need on ship. In this study, existing ships are taken into consideration, and new building ships are excluded. These two items are important while planning to change the fuel system from a conventional fuel system to an alternative fuel system for existing ships.

Table 2.16 is formed to evaluate alternative fuels at adaptability to ships sub-criterions by determining the space and modification needs of each alternative fuels. Table 2.17 includes requirement level scale points which start from 5 to 1, refers to least to highest, respectively. Adaptability to ships evaluation points of alternative fuels is indicated in Table 2.18. These points are given according to their requirements for space and modification on ships. Evaluation points are used at the AHP table for the adaptability to ships sub-criterion.

Table 2.16 : System components of alternative fuel systems.

	Adaptation Requirements	
Alternative Fuels	Space Requirements	Modification Requirements
Ammonia	Storage tank, fuel supply components, GVU, ventilation system	GI block on cylinder covers, special injectors, double walled piping with ventilation
Ethanol	Storage tank, fuel supply components, GVU	LGI block on cylinder covers, special injectors, double walled piping
Hydrogen	Storage tank, fuel supply components, GVU, ventilation system	GI block on cylinder covers, special injectors, double walled piping with ventilation
Kerosene	Storage tank, fuel supply components	Separate injectors and fuel lines
LNG	Storage tank, fuel supply components, GVU, ventilation system	GI block on cylinder covers, special injectors, double walled piping with ventilation
LPG	Storage tank, fuel supply components, GVU, ventilation system	GI block on cylinder covers, special injectors, double walled piping with ventilation
Methanol	Storage tank, fuel supply components, GVU	LGI block on cylinder covers, special injectors, double walled piping

Table 2.17 : Requirement level points.

Requirement Level	Requirement Point
Least	5
Less	4
Moderate	3
Higher	2
Highest	1

Table 2.18 : Adaptability to ships evaluation points of alternative fuels.

Adaptation Requirements	Ammonia	Ethanol	Hydrogen	Kerosene	LNG	LPG	Methanol
Space Requirement	1	2	1	4	1	1	2
Modification Requirement	1	2	1	4	1	1	2
Total Point	2	4	2	8	2	2	4

The third sub-criterion of technical evaluation is the effect on engine components. While considering the positive effects of alternative fuels on engine performance, it has to be considered whether an alternative fuel gives damage to the engine or not. Limited spare part stocks on the ship or unable to repair broken components of the engine, give importance to this sub-criterion.

Table 2.19 shows the effects of alternative fuels on engine components. This information is gotten from the literature review. It can be seen from the tables that alternative fuels, excluding LNG and LPG, have negative effects on stationary and moving parts of the engine.

Table 2.19 : Effects of alternative fuels on engine components.

Alternative Fuels	Effects on Engine Components	References
Ammonia	Very corrosive to copper, brass or bronze materials May cause corrosion on bronze guide ring on piston skirt and some piston gudgeon pins	Pearsall and Garabedian, 1967
Ethanol	Wear at elastomeric components (seals, o-rings) Piston erosion Deterioration of lubricating oil Reduce life-time of exhaust valves and seats Piston ring and liner wear	Hansen et al., 2005; Haraldson, 2014; Shahir et al., 2014
Hydrogen	Shorten the life-time of the combustion chamber components Faster wearing of piston rings	Sroka, 2007; Deniz and Zincir, 2016
Kerosene	Wear at fuel injection pumps and injectors Wear on the moving parts in the combustion system	Anastopoulos et al., 2002; Lee et al., 2007; Patil and Thipse, 2014; Tay et al., 2016; Bayındır et al., 2017
LNG	Negative effects have been unseen Sulfur free structure prevents sulfuric acid formation	Deniz and Zincir, 2016
LPG	Negative effects have been unseen Lubricating oil changing periods have elongated	Raslavicius et al., 2014
Methanol	Wear at elastomeric components (seals, o-rings) Piston erosion Deterioration of lubricating oil Reduce life-time of exhaust valves and seats Piston ring and liner wear	Hansen et al., 2005; Haraldson, 2013; Haraldson, 2014; Shahir et al., 2014

To evaluate alternative fuels at the effect on engine components sub-criterion, Table 2.20 is used. Each alternative fuel gets a matrix point for each component which is affected by them. Table 2.21 shows each effected component’s matrix points. After alternative fuels get matrix points, the mean value of these matrix points was taken to find the effect points of alternative fuels. The effect points of alternative fuels are shown in Table 2.22.

Table 2.20 : Importance- break down period matrix.

		Break down Period		
		Long	Medium	Short
Importance Level	Low	1	3	5
	Moderate	3	5	7
	High	5	7	9

Table 2.21 : Matrix points of engine components.

Component Name	Matrix Levels	Matrix Point
Piston ring	High / Short	9
Lubricating oil	High / Short	9
Fuel injector	High / Medium	7
Fuel injection pump	High / Medium	7
Valves	High / Medium	7
Fuel supply line	Moderate / Medium	5
Filters	Low / Short	5
Rubber components	Moderate / Medium	5
Piston	Moderate / Long	3
Liner	Moderate / Long	3
Piston guide ring	Low /Long	1
Piston gudgeon pin	Low / Long	1

Table 2.22 : Effect points of alternative fuels.

Alternative Fuels	Effect Point
Kerosene	7
Ethanol	6
Methanol	6
Hydrogen	5.8
Ammonia	1
LNG	0
LPG	0

2.4.3.5 Economy

The economy criterion is constituted by commercial effect, investment cost, maintenance cost, and fuel cost. This criterion evaluates alternative fuels by considering the effect of alternative fuel systems on the commercial effect, the investment cost of the alternative fuel systems, the maintenance cost of the alternative fuel systems, and fuel cost.

Commercial effect criterion investigates the effect of alternative fuel system on cargo-carrying space. Especially, fuel storage tanks of alternative fuels occupy large space on ships. This results in a decrease in the cargo-carrying capacity of the ship.

Other system elements of the fuel system can also occupy space, but if it is compared with the fuel tank, occupied space by system elements is insignificant. For this reason, only tanks were taken into consideration in this study.

To compare the commercial effects of alternative fuels, a tank capacity coefficient is calculated for each alternative fuel. It is calculated by using LHV and density values of the alternative fuels. Table 2.23 shows the tank capacity coefficients with the LHVs and densities. LHV values of alternative fuels are first normalized and then inversion of these normalized values is taken. Calculation result gives how much fuel is needed for a unit of the same route for the ship. These numbers can be used for the calculation of the tank capacity coefficient by the division to the density of the alternative fuel. Lower tank capacity coefficient means a better point for commercial effect evaluation weighting.

Table 2.23 : Tank capacity coefficients of alternative fuels.

Alternative Fuels	LHV (MJ/kg)	Density (kg/m^3)	Normalized LHV	Inversion of Normalized LHV	Tank Capacity Coefficient
Ammonia	18.80	682	0.059	17.080	0.025
Ethanol	27.00	794	0.084	11.893	0.015
Hydrogen	119.90	83.8	0.373	2.678	0.032
Kerosene	43.50	775	0.135	7.382	0.010
LNG	46.00	450	0.143	6.980	0.016
LPG	46.00	540	0.143	6.980	0.013
Methanol	19.90	798	0.062	16.136	0.020
References	Reither and Kong, 2008; Negurescu et al., 2012; Putrasari et al., 2013; Zhang et al., 2013a; Parthasarathi et al., 2014; Patil and Thipse, 2014; Deniz and Zincir, 2016; Karagöz et al., 2016; Svensson et al., 2016; Zincir and Deniz, 2016; Zincir et al., 2019				

The investment cost is the initial cost of the application of the alternative fuel system to a ship. Maintenance costs are the costs for periodic or unexpected maintenance of the alternative fuel system.

The investment cost is related to safety, system complexity, and adaptability to ships criterion. For this reason, criteria points that were given to the alternative fuels were used to evaluate alternative fuels at this criterion. Safety, system complexity, and adaptability to ships points will be firstly multiplied with their weightings and the sum of the results of each criteria will be the investment point for the alternative fuels. It will be explained in more detail in the “Results of the Assessment Model” section.

Maintenance cost will be calculated by taking into consideration of system complexity and effect on engine components criteria points of alternative fuels. System complexity points that will be given will be firstly inversed and then normalized. The main purpose of doing this is to provide that lower complexity point means higher complexity level. After then the values will be multiplied with the complexity point weighting. Also, the effect on engine components points of the alternative fuels will be multiplied with its criteria weighting. Values of the system complexity and effect on engine components will be summed for the maintenance cost calculation. It will be explained in more detail in the "Results of the Assessment Model" section.

Fuel cost evaluation of alternative fuels is done by taking into consideration of fuel price and LHV of the alternative fuel. A fuel price coefficient is calculated for each alternative fuel. The calculation is done by normalizing and taking inversion of fuel price firstly. After that, the LHV of alternative fuels is normalized. These values are multiplied to calculate fuel price coefficient of alternative fuel. It is aimed to find the price of the alternative fuel for one unit of distance which depended on fuel price and LHV of the alternative fuel. Table 2.24 shows the fuel cost coefficients of each alternative fuels.

Table 2.24 : Fuel cost coefficients of alternative fuels.

Alternative Fuels	Fuel Price ($/mt)	Normalized Fuel Price	Inversion of Fuel Price	LHV (MJ/kg)	Normalized LHV	Fuel Cost Coefficient
Ammonia	292	0.081	12.404	18.80	0.059	0.726
Ethanol	380	0.105	9.532	27.00	0.084	0.801
Hydrogen	1400	0.387	2.587	119.90	0.373	0.966
Kerosene	596	0.165	6.077	43.50	0.135	0.823
LNG	229	0.063	15.817	46.00	0.143	2.266
LPG	333	0.092	10.877	46.00	0.143	1.558
Methanol	392	0.108	9.240	19.90	0.062	0.573
References	Deniz and Zincir, 2016; Zincir and Deniz, 2016; Zincir et al., 2019; Url 21, Url 22, Url 23, Url 24, Url 25, Url 26, Url 27					

2.4.3.6 Ecology

The ecology criterion is formed by considering emissions of the alternative fuels, global warming potential (GWP), acidity potential (AP) of the alternative fuels, and ecological damage of alternative fuels to the aquatic creatures.

Firstly, the emissions of alternative fuels, GWP, and AP of the alternative fuels are investigated to give points to each alternative fuels. Table 2.25 shows the effects of the alternative fuels on air pollution.

Table 2.25 : Effects of the alternative fuels on air pollution.

Alternative Fuels	CO_2	NO_X	SO_X	CO	PM	HC	GWP	AP	References
Ammonia	-	-	-	+	-	+	-	-	Reiter and Kong, 2008; Reiter and Kong, 2010; Reiter and Kong, 2011; Gil et al., 2012
Ethanol	-	+	-	-	-	+	-	-	Boretti, 2012; Putrasari et al., 2013; Zhang et al., 2013b; Parthasarathi et al., 2014; Zincir and Deniz, 2016
Hydrogen	-	+	-	-	-	+	-	-	Pan et al., 2014; Zhou et al., 2014; Yang et al., 2015; Jhang et al., 2016; Karagöz et al., 2016; Zincir and Deniz, 2016
Kerosene	+	-	-	-	-	+	+	-	Yadav et al., 2005; Bergstrand, 2007; Aydin et al., 2010; Patil and Thipse, 2014; Roy et al., 2014; Solmaz et al., 2016
LNG	-	-	-	+	-	+	-	-	Korakianitis et al.; 2011; Levander, 2011; Cheenkachorn et al., 2013; Deniz and Zincir, 2016; Ghadikolaei et al., 2016; Zincir and Deniz, 2016
LPG	+	-	-	+	-	+	+	-	Saleh, 2008; Kumaraswamy and Prasad, 2012; Neguresсu et al., 2012; Nutu et al., 2014; Chakraborty et al., 2016
Methanol	-	-	-	+	-	+	-	-	Zhang et al., 2013a; Haraldson, 2014; Svensson et al., 2016; Wei et al., 2017; Zincir et al., 2019a; Zincir et al., 2019b

Plus means that the alternative fuel increases the emission amount or GWP or AP and minus means it decreases the emission amount or GWP or AP. This information is taken from previous studies in the literature.

Table 2.26 shows international maritime regulations and ship emission amounts in worldwide. This information is used to form emission matrix points in Table 2.27. The emission matrix points were used in the previous study (Deniz and Zincir, 2016). According to Table 2.27, if an emission type has no global limits and too small emission amount, it receives 1 point. If an emission type has strict global limits and high emission amounts, it receives 12 points.

Table 2.26 : International maritime regulations and ship emission amounts in worldwide (IMO, 2014).

Emission Type	International Maritime Regulations	Emission Amount (tons)
CO_2	MARPOL Annex VI Regulation on Energy Efficiency	938 million
NO_X	MARPOL Annex VI Regulation 13	19000 thousand
SO_X	MARPOL Annex VI Regulation 14	10240 thousand
CO	None	936 thousand
PM	MARPOL Annex VI Regulation 13	1402 thousand
HC	None	Unspecified

Table 2.27 : Emission matrix points (Deniz and Zincir, 2016).

Global Limits	Emission Amount			
	Too small	Small	Moderate	High
No global limits	1	2	3	4
Moderate global limits	2	4	6	8
Strict global limits	3	6	9	12

Table 2.28, emission weight point equivalent of matrix points, was used in the study of Deniz and Zincir, 2016. It is again used in this study to form an emission weight point (EWP) and evaluate alternative fuels.

Table 2.28 : Emission weight point equivalent of matrix points (Deniz and Zincir, 2016).

Emission Type	Matrix Points	Emission Weight Point (EWP) Equivalent
CO_2	12	5
NO_X	9	4
SO_X	9	4
CO	2	2
PM	4	3
HC	1	1

In addition to Table 2.28, Table 2.29 is constituted for the thesis study. It includes EWP for the GWP and AP. EWP for GWP is determined by considering CO_2 emissions while it is determined by considering the mean value of NO_X emission and SO_X emission for AP.

Table 2.29 : Weight points of the GWP and AP.

	Global Warming Potential (GWP)	Acidification Potential (AP)	
	CO_2	NO_X	SO_X
Weight Point	5	4	4
EWP	5	4	

Table 2.30 shows the ecological damage to the aquatic creatures of alternative fuels. It can be seen from the table that hydrogen, LNG, and LPG have no damage to the aquatic creatures. Methanol and ethanol follow them, and ammonia has the highest ecological damage to the aquatic creatures.

Table 2.30 : Ecological damage to the aquatic creatures.

Alternative Fuels	Exposure Rate (LC50 fish mg/l – 96h)	References	Ecological Damage Point (EDP)
Ammonia	0.44	Url 6	1
Ethanol	15300	Url 28	6
Hydrogen	N/A	Url 29	10
Kerosene	33	Url 30	2
LNG	N/A	Url 11	10
LPG	N/A	Url 31	10
Methanol	15400	Url 32	6

Ecology points of the alternative fuels are shown in Table 2.31. Information in Table 2.25 about the effects of alternative fuels on engine emissions are used in Table 2.31. ERP means emission reduction point, AFE means alternative fuel effect, EDP means ecology damage point, and EP_{TOT} means total ecology point. 0 for AFE refers to increasing effect and 1 for AFE refers to decreasing effect. Equations (2.6) and (2.7) are used to calculate ERP_{TOT} (Deniz and Zincir, 2016).

$$\mathbf{ERP_{ij} = EWP_i \ x \ AFE_{ji}} \tag{2.6}$$

$$\mathbf{EP_{j,TOT} = \sum ERP_{ij} + EDP_i} \tag{2.7}$$

Where ERP_{ij} means emission reduction point of i type of emission of j type of alternative fuel, EWP_i means emission weight point of i type of emission, AFE_{ji} means alternative fuel effect of j type of alternative fuel on i type of emission, ERP_{ij}

means emission reduction point of i type of emission and j type of alternative fuel, EDP_i means ecology damage point of i type of alternative fuel, and $EP_{j,TOT}$ means total emission reduction point of j type of emission.

According to Table 2.31, LNG has the highest $EP_{j,TOT}$ of 35 which means it gives the least damage to the ecology. Hydrogen is the second and methanol is the third alternative fuel with 33 and 31, respectively. Kerosene has the lowest point of 19 which results in the highest ecology damage if it is used on ships as a fuel.

Table 2.31 : Ecology points of the alternative fuels.

Alternative Fuels	Emission Types												GWP (5)		AP (4)		EDP	EP_{TOT}
	CO_2 (5)		NO_X (4)		SO_X (4)		CO (2)		PM (3)		HC (1)							
	AFE	ERP	AFE	ERP	AFE	ERP	AFE	ERP	AFE	ERP	AFE	ERP	AFE	ERP	AFE	ERP		
Ammonia	1	5	1	4	1	4	0	0	1	3	0	0	1	5	1	4	1	26
Ethanol	1	5	0	0	1	4	1	2	1	3	0	0	1	5	1	4	6	29
Hydrogen	1	5	0	0	1	4	1	2	1	3	0	0	1	5	1	4	10	33
Kerosene	0	0	1	4	1	4	1	2	1	3	0	0	0	0	1	4	2	19
LNG	1	5	1	4	1	4	0	0	1	3	0	0	1	5	1	4	10	35
LPG	0	0	1	4	1	4	0	0	1	3	0	0	0	0	1	4	10	25
Methanol	1	5	1	4	1	4	0	0	1	3	0	0	1	5	1	4	6	31

3. RESULTS OF THE ASSESSMENT MODEL

In this section, the weighting of the main criterion and weighting of the sub-criterion is calculated. The AHP method is used to calculate the weightings. After the determination of the weightings, the final performance of the alternative fuels is obtained.

3.1 Weightings of the Main Criteria

To calculate the weighting of the main criterion, a survey was prepared and asked the fourteen experts. Five of these experts were from Lund University, Division of Combustion Engines, seven of these experts were the academicians of Istanbul Technical University Maritime Faculty and the remaining of these experts from the maritime industry.

The main criteria were included in the survey and asked experts to give points from 1 to 5 for each criterion. 1 was the least important and 5 was the most important criterion for shipboard usage of the alternative fuels. They could give the same point to different criteria. Survey points can be found in Appendices, Table A1. After finding the expert points for each criterion, the highest point difference between the criterion was attained and divided to 9 for determining the relative importance point intervals, because there are 9 relative importance points which were indicated in Table 2.4. This method helped to do a pair-wise comparison between the criterion and it was used at previous studies (Deniz and Zincir, 2016; Zincir and Deniz, 2018a). The process can be followed by Tables A2 to A4 in Appendices. The relative importance of a criterion to another criterion was found according to the point difference between them. After then, the relative importance points of the criteria were determined. The main criterion weightings were calculated by using AHP and it was shown in Table 3.1.

Table 3.1 : The main criteria weightings.

Criterion	Safety	Ecology	Legislation	Reliability	Economy	Technical	Weighting
Safety	1.00	1.00	3.00	5.00	7.00	9.00	0.346
Ecology	1.00	1.00	3.00	5.00	7.00	9.00	0.346
Legislation	0.33	0.33	1.00	2.00	4.00	6.00	0.146
Reliability	0.20	0.20	0.50	1.00	3.00	5.00	0.090
Economy	0.14	0.14	0.25	0.33	1.00	3.00	0.046
Technical	0.11	0.11	0.17	0.20	0.33	1.00	0.025
λ_{max} = 6.163, CI = 0.033, CR = 0.026 < 0.1							

It can be seen that the safety and the ecology criterion had the highest weighting of 0.346. The legislation criterion was the third important criteria for the experts with the weighting of 0.146. The weighting of the reliability, economy, and technical were 0.090, 0.046, and 0.025, respectively.

3.2 Weightings of the Sub-criteria

The legislation and ecology main criteria were not had sub-criteria for this reason, they were not asked the experts.

The safety main criterion was investigated in the previous study of Zincir and Deniz, (2018a). In addition to the sub-criterion of the safety criteria in this thesis, density was also a sub-criterion in the previous study. The expert opinions were taken and the AHP method was used in that study to find the weightings of the sub-criterion. Table 3.2 shows the weightings of safety sub-criterion. It was observed in the study that the density sub-criterion had the least weighting with 0.021. The density sub-criterion did not have much influence on the results, for this reason, it was not included in the thesis study. The weighting of the density sub-criterion was distributed equally to the other sub-criterion. The new weightings of the safety sub-criterion were again shown in Table 3.2.

Table 3.2 : The safety sub-criteria weightings.

Criterion	Previous Weightings	New Weightings
Flashpoint	0.315	0.319
Exposure rate	0.315	0.319
Auto-ignition	0.207	0.211
Flammability limit	0.071	0.075
Flame Speed	0.071	0.075
Density	0.021	-

The reliability main criteria had sub-criteria of maturity and bunkering capability. The AHP method cannot be applied when the criteria numbers are less than three. For this reason, their expert points were compared with each other and the weightings were determined. According to the comparison result, the maturity sub-criterion got 0.466 while the bunkering capability sub-criterion earned 0.534.

The technical main criterion had three sub-criteria. This sub-criteria were the system complexity, adaptability to ships, and effect on engine components. After getting expert opinions, pair-wise comparison of the sub-criterion was made and the AHP method was used to find the weightings of the sub-criterion. The process can be followed by Table A5 to A7 in Appendices. The weightings of the technical main criteria were shown in Table 3.3. The effect on engine components received the highest point from the experts and got the weighting of 0.655. The adaptability to ships sub-criteria had 0.290 and the system complexity had 0.055 which was least important for the experts.

Table 3.3 : The technical sub-criteria weightings.

Criterion	Effect on engine components	Adaptability to ships	System complexity	Weighting
Effect on engine components	1.00	3.00	9.00	0.655
Adaptability to ships	0.33	1.00	7.00	0.290
System complexity	0.11	0.14	1.00	0.055

$\lambda_{max} = 3.08$, CI = 0.04, CR = 0.077 < 0.1

The economy main criterion had four sub-criteria. This sub-criteria were the commercial effect, investment cost, maintenance cost, and fuel cost. According to the expert opinions and application of the AHP method afterward, the fuel cost received the highest weighting of 0.729. The commercial effect and the maintenance cost sub-criteria had the same weighting of 0.105. The investment cost was the least important economy sub-criterion with the weighting of 0.061. The calculation process can be followed by Table A8 to A10 in Appendices. The AHP table of the economy sub-criteria weightings was shown in Table 3.4.

Table 3.4 : The economy sub-criteria weightings.

Criterion	Fuel cost	Commercial effect	Maintenance cost	Investment cost	Weighting
Fuel cost	1.00	8.00	8.00	9.00	0.729
Commercial effect	0.13	1.00	1.00	2.00	0.105
Maintenance cost	0.13	100	1.00	2.00	0.105
Investment cost	0.11	0.50	0.50	1.00	0.061
λ_{max} = 4.05, CI = 0.02, CR = 0.019 < 0.1					

3.3 Weightings of the Alternative Fuels

This section includes the weightings of the alternative fuels at each evaluation criterion. The performance of the alternative fuels was evaluated for each main criterion. The same method, which was used to determine the weightings of the main criterion and sub-criterion, was used to find the weightings of the alternative fuels at each criterion.

3.3.1 The safety weightings of the alternative fuels

The safety performance assessment of alternative fuels was done by evaluating them at flashpoint, auto-ignition, lower explosive limit (LEL), upper explosive limit (UEL), flame speed, and exposure rate sub-criterion. The specifications of the alternative fuels in Table 2.2 were used to do a pair-wise comparison of alternative fuels. The calculation process for the safety weightings can be followed by Table A11 to Table A28 in Appendices.

Table 3.5 shows the flashpoint evaluation and the weightings of alternative fuels. It can be seen that ammonia has the highest weighting of 0.404 which means it is the safest alternative fuel with respect to the flashpoint sub-criterion. Kerosene is the second safest, ethanol and methanol are the third safest alternative fuels with 0.175 and 0.155, respectively. LNG has the least weighting due to its lowest flashpoint value which results in higher safety concerns on a ship.

Table 3.5 : The flashpoint weightings of the alternative fuels.

Alternative	Ammonia	Kerosene	Ethanol	Methanol	LPG	Hydrogen	LNG	Weighting
Ammonia	1.00	3.00	4.00	4.00	7.00	8.00	9.00	0.404
Kerosene	0.33	1.00	1.00	1.00	5.00	6.00	7.00	0.175
Ethanol	0.25	1.00	1.00	1.00	4.00	5.00	6.00	0.155
Methanol	0.25	1.00	1.00	1.00	4.00	5.00	6.00	0.155
LPG	0.14	0.20	0.25	0.25	1.00	2.00	3.00	0.050
Hydrogen	0.13	0.17	0.20	0.20	0.50	1.00	2.00	0.035
LNG	0.11	0.14	0.17	0.17	0.33	0.50	1.00	0.025
	λ_{max} = 7.286, CI = 0.048, CR = 0.035 < 0.1							

The auto-ignition weightings of alternative fuels are shown in Table 3.6. Ammonia has the highest weighting of 0.358, hydrogen has the second-highest and LNG has the third-highest weighting with 0.215 and 0.172, respectively. The lower safety concern is expected while using these alternative fuels as the main engine fuel. Kerosene has the lowest auto-ignition weighting of 0.021, which affects safety concerns and increases safety precautions on a ship.

Table 3.6 : The auto-ignition weightings of the alternative fuels.

Alternative	Ammonia	Hydrogen	LNG	Methanol	LPG	Ethanol	Kerosene	Weighting
Ammonia	1.00	2.00	3.00	4.00	5.00	6.00	9.00	0.358
Hydrogen	0.50	1.00	1.00	3.00	3.00	5.00	8.00	0.215
LNG	0.33	1.00	1.00	2.00	2.00	4.00	7.00	0.172
Methanol	0.25	0.33	0.50	1.00	1.00	3.00	6.00	0.098
LPG	0.20	0.33	0.50	1.00	1.00	2.00	5.00	0.087
Ethanol	0.17	0.20	0.25	0.33	0.50	1.00	4.00	0.049
Kerosene	0.11	0.13	0.14	0.17	0.20	0.25	1.00	0.021
	λ_{max} = 7.208, CI = 0.035, CR = 0.026 < 0.1							

The lower explosion limit (LEL) and the upper explosion limit (UEL) are shown in Table 3.7 and 3.8. These values are important if there is a leakage at the fuel tanks. The limits indicate the required fuel concentration in the air start to the combustion event which can result in the explosion.

Table 3.7 : The LEL weightings of the alternative fuels.

Alternative	Ammonia	Methanol	LNG	Hydrogen	Ethanol	LPG	Kerosene	Weighting
Ammonia	1.00	6.00	7.00	7.00	8.00	9.00	9.00	0.537
Methanol	0.17	1.00	1.00	2.00	2.00	3.00	4.00	0.127
LNG	0.14	1.00	1.00	1.00	2.00	2.00	3.00	0.102
Hydrogen	0.14	0.50	1.00	1.00	1.00	2.00	3.00	0.084
Ethanol	0.13	0.50	0.50	1.00	1.00	1.00	2.00	0.064
LPG	0.11	0.33	0.50	0.50	1.00	1.00	1.00	0.048
Kerosene	0.11	0.25	0.33	0.33	0.50	1.00	1.00	0.038
	λ_{max} = 7.190, CI = 0.032, CR = 0.023 < 0.1							

Ammonia, methanol, and LNG are the top three alternative fuels with the weightings of 0.537, 0.127, and 0.102, respectively. These fuels create lesser safety concerns than other fuels. On the other hand, kerosene, LPG, and LNG are the top three alternative fuels at the UEL weightings with 0.263, 0.225, and 0.174, respectively, in Table 3.8.

Table 3.8 : The UEL weightings of the alternative fuels.

Alternative	Kerosene	LPG	LNG	Ethanol	Ammonia	Methanol	Hydrogen	Weighting
Kerosene	1.00	1.00	2.00	2.00	3.00	4.00	9.00	0.263
LPG	1.00	1.00	1.00	2.00	2.00	4.00	9.00	0.225
LNG	0.50	1.00	1.00	1.00	2.00	3.00	8.00	0.174
Ethanol	0.50	0.50	1.00	1.00	1.00	3.00	8.00	0.143
Ammonia	0.33	0.50	0.50	1.00	1.00	2.00	7.00	0.113
Methanol	0.25	0.25	0.33	0.33	0.50	1.00	6.00	0.064
Hydrogen	0.11	0.11	0.13	0.13	0.14	0.17	1.00	0.019
	λ_{max} = 7.149, CI = 0.025, CR = 0.018 < 0.1							

Table 3.9 includes the flame speed weightings of alternative fuels. The flame speed of the alternative fuels is again very important if there is a leakage at the fuel tanks. It can give a clue about the spreading rate of the fire on a ship. Ammonia has the highest weighting of 0.199 which means it has the lowest flame speed value. LNG, LPG, and ethanol have a weighting of 0.164 which follows ammonia. These fuels have the same weighting and similar flame speed. Hydrogen has the least weighting of 0.019 which is remarkably low when it is compared with the other alternative fuels. It can be expected that the hydrogen fuel flames spread extremely fast in a ship during a fire incident.

Table 3.9 : The flame speed weightings of the alternative fuels.

Alternative	Ammonia	LNG	LPG	Ethanol	Methanol	Kerosene	Hydrogen	Weighting
Ammonia	1.00	1.00	1.00	1.00	2.00	2.00	9.00	0.199
LNG	1.00	1.00	1.00	1.00	1.00	1.00	9.00	0.164
LPG	1.00	1.00	1.00	1.00	1.00	1.00	9.00	0.164
Ethanol	1.00	1.00	1.00	1.00	1.00	1.00	9.00	0.164
Methanol	0.50	1.00	1.00	1.00	1.00	1.00	8.00	0.146
Kerosene	0.50	1.00	1.00	1.00	1.00	1.00	8.00	0.146
Hydrogen	0.11	0.11	0.11	0.11	0.13	0.13	1.00	0.019
	λ_{max} = 7.088, CI = 0.015, CR = 0.011 < 0.1							

The exposure rate in a working environment is an important parameter for human health. Although there can be precautions to prevent the vaporization of the fuel in the enclosed spaces on the ships, there is a possibility of vaporization of the fuel. The exposure rate indicates the maximum exposure level to alternative fuels while doing fuel operations. The exposure rate weightings of the alternative fuels are shown in

Table 3.10. It can be seen that ethanol and LPG have the highest weighting of 0.375, which fuels have a lesser effect on human health. On the other hand, kerosene, methanol, and ammonia have lower weightings of 0.038, 0.038, and 0.033, respectively. More precautions should be taken while doing operations with these alternative fuels, including protective clothes, masks, breathing equipment, etc.

Table 3.10 : The exposure rate weightings of the alternative fuels.

Alternative	Ethanol	LPG	LNG	Hydrogen	Kerosene	Methanol	Ammonia	Weighting
Ethanol	1.00	1.00	6.00	8.00	9.00	9.00	9.00	0.375
LPG	1.00	1.00	6.00	8.00	9.00	9.00	9.00	0.375
LNG	0.17	0.17	1.00	2.00	3.00	3.00	4.00	0.093
Hydrogen	0.13	0.13	0.50	1.00	1.00	1.00	2.00	0.046
Kerosene	0.11	0.11	0.33	1.00	1.00	1.00	1.00	0.038
Methanol	0.11	0.11	0.33	1.00	1.00	1.00	1.00	0.038
Ammonia	0.11	0.11	0.25	0.50	1.00	1.00	1.00	0.033
	$\lambda_{max} = 7.130$, CI = 0.022, CR = 0.016 < 0.1							

The safety performance weightings of alternative fuels are shown in Table 3.11. The weightings are calculated by equation (3.1). Where W_{S_i} is the safety performance weighting of i type of alternative fuel, $w_{i_{j1}}$ to $w_{i_{j6}}$ are the weightings of i type of alternative fuel at j1 to j6 evaluation sub-criteria of the safety criterion, $w_{s_{j1}}$ to $w_{s_{j6}}$ are the weightings of the evaluation sub-criteria.

$$\mathbf{W_{S_i}} = \left(\mathbf{w_{i_{j1}} x\, w_{s_{j1}}}\right) + \left(\mathbf{w_{i_{j2}} x\, w_{s_{j2}}}\right) + \left(\mathbf{w_{i_{j3}} x\, w_{s_{j3}}}\right) + \left(\mathbf{w_{i_{j4}} x\, w_{s_{j4}}}\right) + \left(\mathbf{w_{i_{j5}} x\, w_{s_{j5}}}\right) + \left(\mathbf{w_{i_{j6}} x\, w_{s_{j6}}}\right) \quad (3.1)$$

According to the calculations, it is found that ammonia has the highest safety performance weightings of 0.255 which mean there is the least safety concern on a ship if this fuel is used onboard. Ethanol is the second alternative fuel with the weighting of 0.200 and LPG is the third with the weighting of 0.177.

Table 3.11 : The safety performance weightings of the alternative fuels.

Alternative Fuels	Flashpoint (0.319)	Auto-ignition (0.211)	LEL (0.0375)	UEL (0.0375)	Flame Speed (0.075)	Exposure Rate (0.319)	Weighting
Ammonia	0.404	0.358	0.537	0.113	0.199	0.033	0.255
Ethanol	0.155	0.049	0.064	0.143	0.164	0.375	0.200
Hydrogen	0.035	0.215	0.084	0.019	0.019	0.046	0.077
Kerosene	0.175	0.021	0.038	0.263	0.146	0.038	0.095
LNG	0.025	0.172	0.102	0.174	0.164	0.093	0.097
LPG	0.050	0.087	0.048	0.225	0.164	0.375	0.177
Methanol	0.155	0.098	0.127	0.064	0.146	0.038	0.100

3.3.2 The legislation weightings of the alternative fuels

The alternative fuels are pair-wise compared with each other by using their received points from by complying with NO_X Technical Code, SO_X Regulation, Energy Efficiency for Ships Regulation, IGF Code, STCW, MRV Regulation, and IMO DCS. The same method, which was used to determine the weightings of the main criterion and sub-criterion, was used to find the weightings of alternative fuels at each criterion. The calculation process can be followed by Table A29 to A31 in Appendices.

Table 3.12 shows the legislation performance weightings of alternative fuels. It is observed that LNG has the highest legislation weighting of 0.194 which means it complies more with the international maritime rules and regulations than the other alternative fuels without additional applications. Ammonia, methanol, ethanol, and hydrogen have an equal weighting of 0.190. They need slightly higher precautions, training, and applications than LNG to comply with international maritime rules and regulations. Kerosene and LPG show a lower legislation performance which means higher precautions, training, and applications are needed to comply with the international maritime rules and regulations.

Table 3.12 : The legislation performance weightings of the alternative fuels.

Alternative	LNG	Ammonia	Methanol	Ethanol	Hydrogen	Kerosene	LPG	Weighting
LNG	1.00	1.00	1.00	1.00	1.00	9.00	9.00	0.194
Ammonia	1.00	1.00	1.00	1.00	1.00	8.00	9.00	0.190
Methanol	1.00	1.00	1.00	1.00	1.00	8.00	9.00	0.190
Ethanol	1.00	1.00	1.00	1.00	1.00	8.00	9.00	0.190
Hydrogen	1.00	1.00	1.00	1.00	1.00	8.00	9.00	0.190
Kerosene	0.11	0.13	0.13	0.13	0.13	1.00	1.00	0.023
LPG	0.11	0.11	0.11	0.11	0.11	1.00	1.00	0.022
	λ_{max} = 7.001, CI = 0.0002, CR = 0 < 0.1							

3.3.3 The reliability weightings of the alternative fuels

The reliability performance weightings of the alternative fuels are determined according to the pair-wise comparison of the alternative fuels at the maturity and the bunkering capability sub-criteria of the reliability main criteria. The same method, which was used to determine the weightings of the main criterion and sub-criterion, was used to find the weightings of the alternative fuels at each criterion. The calculation process can be followed by Table A32 to A37 in Appendices.

Table 3.13 shows the maturity weightings of alternative fuels. It can be seen that LNG has the dominant weighting point with 0.434. There are many commercial ships fuelled with LNG that increases its maturity level. LPG and methanol have a weighting of 0.190. These alternative fuels are the second mature fuels for shipboard usage. Ammonia and kerosene are the least mature alternative fuels with the weighting of 0.025.

Table 3.13 : The maturity weightings of the alternative fuels.

Alternative	LNG	LPG	Methanol	Ethanol	Hydrogen	Kerosene	Ammonia	Weighting
LNG	1.00	4.00	4.00	7.00	7.00	9.00	9.00	0.434
LPG	0.25	1.00	1.00	4.00	4.00	7.00	7.00	0.190
Methanol	0.25	1.00	1.00	4.00	4.00	7.00	7.00	0.190
Ethanol	0.14	0.25	0.25	1.00	1.00	4.00	4.00	0.068
Hydrogen	0.14	0.25	0.25	1.00	1.00	4.00	4.00	0.068
Kerosene	0.11	0.14	0.14	0.25	0.25	1.00	1.00	0.025
Ammonia	0.11	0.14	0.14	0.25	0.25	1.00	1.00	0.025

λ_{max} = 7.485, CI = 0.081, CR = 0.060< 0.1

Table 3.14 shows the bunkering capability weightings of alternative fuels. Methanol is dominant at the weightings with 0.446. Methanol is an important substance for the chemical industry and a large amount of methanol is produced worldwide which increases the availability of the methanol bunkering in various ports. Kerosene is the second alternative fuel with the weighting of 0.239, and LNG and LPG are the third with the weighting of 0.104. The least bunkering capable alternative fuels are ethanol and hydrogen according to the weighting of 0.031.

Table 3.14 : The bunkering capability weightings of the alternative fuels.

Alternative	Methanol	Kerosene	LNG	LPG	Ammonia	Ethanol	Hydrogen	Weighting
Methanol	1.00	3.00	6.00	6.00	8.00	9.00	9.00	0.446
Kerosene	0.33	1.00	3.00	3.00	6.00	7.00	7.00	0.239
LNG	0.17	0.33	1.00	1.00	3.00	4.00	4.00	0.104
LPG	0.17	0.33	1.00	1.00	3.00	4.00	4.00	0.104
Ammonia	0.13	0.17	0.33	0.33	1.00	2.00	2.00	0.046
Ethanol	0.11	0.14	0.25	0.25	0.50	1.00	1.00	0.031
Hydrogen	0.11	0.14	0.25	0.25	0.50	1.00	1.00	0.031

λ_{max} = 7.314, CI = 0.052, CR = 0.039< 0.1

The reliability performance weightings of the alternative fuels are calculated by equation (3.2) and they are shown in Table 3.11.

$$\mathbf{W_{R_i}} = \left(\mathbf{w_{i_{j1}} x\, w_{r_{j1}}}\right) + \left(\mathbf{w_{i_{j2}} x\, w_{r_{j2}}}\right) \tag{3.2}$$

Where $\mathbf{W}_{\mathbf{R}_\mathbf{i}}$ is the reliability performance weighting of i type of alternative fuel, $\mathbf{w}_{\mathbf{i}_{\mathbf{j1}}}$ and $\mathbf{w}_{\mathbf{i}_{\mathbf{j2}}}$ are the weightings of i type of alternative fuel at j1 and j2 evaluation sub-criterion of the reliability criterion, $\mathbf{w}_{\mathbf{r}_{\mathbf{j1}}}$ and $\mathbf{w}_{\mathbf{r}_{\mathbf{j2}}}$ are the weightings of the evaluation sub-criteria.

It can be seen in Table 3.11 that methanol has the highest reliability performance with the weighting of 0.327. LNG has the second-highest reliability performance with 0.258 and LPG is the third with 0.144. Ammonia has the least reliability performance by its weighting of 0.036.

Table 3.15 : The reliability performance weightings of the alternative fuels.

Alternative Fuels	Maturity (0.466)	Bunkering Capability (0.534)	Weighting
Ammonia	0.025	0.046	0.036
Ethanol	0.068	0.031	0.048
Hydrogen	0.068	0.031	0.048
Kerosene	0.025	0.239	0.139
LNG	0.434	0.104	0.258
LPG	0.190	0.104	0.144
Methanol	0.190	0.446	0.327

3.3.4 The technical weightings of the alternative fuels

The technical weightings of the alternative fuels are determined by the pair-wise comparison of the alternative fuels at the system complexity, adaptability to ships, and effect on engine components sub-criteria. The same method, which was used to determine the weightings of the main criterion and sub-criterion, was used to find the weightings of the alternative fuels at each criterion. The calculation process can be followed by Table A38 to A46 in Appendices.

The system complexity weightings of the alternative fuels are shown in Table 3.16. Kerosene has the highest weighting of 0.488 which means that it has the least system complexity and system equipment number. Ethanol and methanol fuel systems are the second least complex systems and they get the weighting of 0.175. The remaining alternative fuels have the same weighting of 0.040 that these alternative fuels require more complex fuel systems to operate the main engine with these fuels.

Table 3.16 : The system complexity weightings of the alternative fuels.

Alternative	Kerosene	Ethanol	Methanol	Ammonia	Hydrogen	LNG	LPG	Weighting
Kerosene	1.00	5.00	5.00	9.00	9.00	9.00	9.00	0.488
Ethanol	0.20	1.00	1.00	5.00	5.00	5.00	5.00	0.175
Methanol	0.20	1.00	1.00	5.00	5.00	5.00	5.00	0.175
Ammonia	0.11	0.20	0.20	1.00	1.00	1.00	1.00	0.040
Hydrogen	0.11	0.20	0.20	1.00	1.00	1.00	1.00	0.040
LNG	0.11	0.20	0.20	1.00	1.00	1.00	1.00	0.040
LPG	0.11	0.20	0.20	1.00	1.00	1.00	1.00	0.040

λ_{max} = 7.356, CI = 0.059, CR = 0.044< 0.1

Table 3.17 shows the adaptability to ships weightings of alternative fuels. Kerosene has a similar fuel supply system and simple adaptability requirements. For this reason, it gets a dominant weighting of 0.538. Ethanol and methanol follow kerosene after with the weighting of 0.133. The remaining alternative fuels have the same weighting of 0.049. They require a high level of modification on a ship to convert the ship or new building of a ship as fuelled with these alternative fuels.

Table 3.17 : The adaptability to ships weightings of the alternative fuels.

Alternative	Kerosene	Ethanol	Methanol	Ammonia	Hydrogen	LNG	LPG	Weighting
Kerosene	1.00	6.00	6.00	9.00	9.00	9.00	9.00	0.538
Ethanol	0.17	1.00	1.00	3.00	3.00	3.00	3.00	0.133
Methanol	0.17	1.00	1.00	3.00	3.00	3.00	3.00	0.133
Ammonia	0.11	0.33	0.33	1.00	1.00	1.00	1.00	0.049
Hydrogen	0.11	0.33	0.33	1.00	1.00	1.00	1.00	0.049
LNG	0.11	0.33	0.33	1.00	1.00	1.00	1.00	0.049
LPG	0.11	0.33	0.33	1.00	1.00	1.00	1.00	0.049

λ_{max} = 7.166, CI = 0.028, CR = 0.020< 0.1

Table 3.18 shows the effect on engine components weightings of alternative fuels. LNG and LPG have the highest weighting of 0.318 which means they have the least negative effect on engine components. Ammonia follows them with the weighting of 0.219. Kerosene has the least weighting of 0.025 which means it can give the highest damage to the engine components.

Table 3.18 : The effect on engine components weightings of the alternative fuels.

Alternative	LNG	LPG	Ammonia	Hydrogen	Methanol	Ethanol	Kerosene	Weighting
LNG	1.00	1.00	2.00	8.00	8.00	8.00	9.00	0.318
LPG	1.00	1.00	2.00	8.00	8.00	8.00	9.00	0.318
Ammonia	0.50	0.50	1.00	7.00	7.00	7.00	8.00	0.219
Hydrogen	0.13	0.13	0.14	1.00	1.00	1.00	2.00	0.040
Methanol	0.13	0.13	0.14	1.00	1.00	1.00	2.00	0.040
Ethanol	0.13	0.13	0.14	1.00	1.00	1.00	2.00	0.040
Kerosene	0.11	0.11	0.13	0.50	0.50	0.50	1.00	0.025

λ_{max} = 7.122, CI = 0.020, CR = 0.015< 0.1

The reliability performance weightings of the alternative fuels are calculated by equation (3.3) and they are shown in Table 3.19.

$$\mathbf{W_{T_i}} = \left(\mathbf{w_{i_{j1}} x\, w_{t_{j1}}}\right) + \left(\mathbf{w_{i_{j2}} x\, w_{t_{j2}}}\right) + \left(\mathbf{w_{i_{j3}} x\, w_{t_{j3}}}\right) \tag{3.3}$$

Where W_{T_i} is the technical performance weighting of i type of alternative fuel, $w_{i_{j1}}$, $w_{i_{j2}}$, and $w_{i_{j3}}$ are the weightings of i type of alternative fuel at j1, j2, and j3 evaluation sub-criterion of the reliability criterion, $w_{t_{j1}}$, $w_{t_{j2}}$, and $w_{t_{j3}}$ are the weightings of the evaluation sub-criteria.

Table 3.19 shows the technical performance weightings of alternative fuels. LNG and LPG have the highest technical performance weightings of 0.225 after the evaluation result. Kerosene is the second one with the weighting of 0.199 and ammonia is the third one with the weighting of 0.160. Ethanol and methanol have the lowest technical performance weighting of 0.074.

Table 3.19 : The technical performance weightings of the alternative fuels.

Alternative Fuels	System Complexity (0.055)	Adaptability to Ships (0.290)	Effect on Engine Components (0.655)	Weighting
Ammonia	0.040	0.049	0.219	0.160
Ethanol	0.175	0.133	0.040	0.074
Hydrogen	0.040	0.049	0.040	0.043
Kerosene	0.488	0.538	0.025	0.199
LNG	0.040	0.049	0.318	0.225
LPG	0.040	0.049	0.318	0.225
Methanol	0.175	0.133	0.040	0.074

3.3.5 The economy weightings of the alternative fuels

The economy weightings of the alternative fuels are calculated by the pair-wise comparison of the fuels under the commercial effect, investment cost, maintenance cost, and fuel cost sub-criteria. The same method, which was used to determine the weightings of the main criterion and sub-criterion, was used to find the weightings of the alternative fuels at each criterion. The calculation process can be followed by Table A47 to A58 in Appendices.

The commercial effect weightings of the alternative fuels are calculated by using the tank capacity coefficients of the alternative fuels which are shown in Table 2.23 and the weightings are shown in Table 3.20. It can be seen that kerosene has the highest weighting of 0.350 that occupies the least tank space and it results in the lowest commercial effect on a ship. LPG is the second and ethanol is the third alternative fuel with 0.201 and 0.169, respectively. Hydrogen has the lowest weighting of 0.022 which means it requires larger storage tanks that result in a higher commercial effect on a ship.

Table 3.20 : The commercial effect weightings of the alternative fuels.

Alternative	Kerosene	LPG	Ethanol	LNG	Methanol	Ammonia	Hydrogen	Weighting
Kerosene	1.00	2.00	3.00	3.00	5.00	7.00	9.00	0.350
LPG	0.50	1.00	1.00	2.00	3.00	5.00	8.00	0.201
Ethanol	0.33	1.00	1.00	1.00	3.00	5.00	7.00	0.169
LNG	0.33	0.50	1.00	1.00	2.00	4.00	7.00	0.140
Methanol	0.20	0.33	0.33	0.50	1.00	3.00	5.00	0.079
Ammonia	0.14	0.20	0.20	0.25	0.33	1.00	3.00	0.040
Hydrogen	0.11	0.13	0.14	0.14	0.20	0.33	1.00	0.022
	λ_{max} = 7.202, CI = 0.034, CR = 0.025< 0.1							

The investment cost weightings of the alternative fuels are calculated by using the investment point of the alternative fuels (IP_i) in Table 3.21. To calculate the investment points of the alternative fuels, equation (3.4) and the weightings in Table 3.21 is used.

$$\mathbf{IP_i = w_{i_{j1}} x \left(w_{t_{j1}} x\, W_{C_T}\right) + w_{i_{j2}} x \left(w_{t_{j2}} x\, W_{C_T}\right) + W_{S_i} x\, W_{C_S}} \qquad (3.4)$$

Where IP_i is the investment point, $w_{i_{j1}}$ and $w_{i_{j2}}$ are the weightings of i type of alternative fuel at j1 and j2 sub-criterion of the technical criteria, $w_{t_{j1}}$ and $w_{t_{j2}}$ are the weightings of the technical sub-criteria of system complexity and adaptability to ships, respectively, W_{C_T} is the weighting of the technical criteria, W_{S_i} is the safety weighting of i type of alternative fuel, and W_{C_S} is the weighting of safety criteria.

Table 3.21 : The investment point of the alternative fuels.

Alternative Fuels	System Complexity (0.001375)	Adaptability to Ships (0.00725)	Safety (0.346)	Investment Point
Ammonia	0.040	0.049	0.255	0.0886
Ethanol	0.175	0.133	0.200	0.0704
Hydrogen	0.040	0.049	0.077	0.0271
Kerosene	0.488	0.538	0.095	0.0374
LNG	0.040	0.049	0.097	0.0340
LPG	0.040	0.049	0.177	0.0617
Methanol	0.175	0.133	0.100	0.0358

Table 3.22 shows the investment cost weightings of alternative fuels. It can be seen that ammonia has the highest weighting of 0.431 which means the fuel system needs the lowest investment cost to apply on a ship. Ethanol is the second and LPG is the third alternative fuels with the weightings of 0.237 and 0.162, respectively. Hydrogen has the lowest weighting of 0.029 that requires the highest investment cost.

Table 3.22 : The investment cost weightings of the alternative fuels.

Alternative	Ammonia	Ethanol	LPG	Kerosene	Methanol	LNG	Hydrogen	Weighting
Ammonia	1.00	3.00	4.00	8.00	8.00	8.00	9.00	0.431
Ethanol	0.33	1.00	2.00	5.00	6.00	6.00	7.00	0.237
LPG	0.25	0.50	1.00	4.00	4.00	5.00	6.00	0.162
Kerosene	0.13	0.20	0.25	1.00	1.00	1.00	2.00	0.048
Methanol	0.13	0.17	0.25	1.00	1.00	1.00	2.00	0.047
LNG	0.13	0.17	0.20	1.00	1.00	1.00	2.00	0.046
Hydrogen	0.11	0.14	0.17	0.50	0.50	0.50	1.00	0.029
	$\lambda_{max} = 7.264$, CI = 0.044, CR = 0.033< 0.1							

The maintenance cost weightings of the alternative fuels are calculated by the assist of the maintenance points of each alternative fuel. The maintenance points are found by using equation (3.5) and values in Table 3.23. After finding the maintenance points, the pair-wise comparison is done to find the weightings.

$$\mathbf{MP_i} = \left(\mathbf{N_{ISC_i}\,x\,W_{SC_{SC}}}\right) + \left(\mathbf{W_{e_i}\,x\,W_{SC_E}}\right) \tag{3.5}$$

Where MP_i is the maintenance point of the i type of alternative fuel, N_{ISC_i} is the normalized point of inversed system complexity weighting of i type of alternative fuel, W_{SC_C} is the weighting of the sub-criterion of the system complexity, W_{e_i} is the effect on engine components weighting of I type of alternative fuel, and W_{SC_E} is the weighting of the sub-criterion of the effect on engine components.

Table 3.23 : The maintenance point of the alternative fuels.

Alternative Fuels	System Complexity	Inversed System Complexity	Normalized System Complexity	Effect on Engine Components	Maintenance Point
Ammonia	0.040	25.000	0.220	0.219	0.156
Ethanol	0.175	5.714	0.050	0.040	0.029
Hydrogen	0.040	25.000	0.220	0.040	0.038
Kerosene	0.488	2.049	0.018	0.025	0.017
LNG	0.040	25.000	0.220	0.318	0.220
LPG	0.040	25.000	0.220	0.318	0.220
Methanol	0.175	5.714	0.050	0.040	0.029

Table 3.24 shows the maintenance cost weighting of alternative fuels. LNG and LPG have the same weighting of 0.344. They have the lowest maintenance cost if they are used on a ship. Ammonia has the weighting of 0.174, after LNG and LPG. Kerosene has the lowest weighting of 0.034, which means there will be the highest maintenance cost if it is used on a ship.

Table 3.24 : The maintenance cost weightings of the alternative fuels.

Alternative	LNG	LPG	Ammonia	Hydrogen	Ethanol	Methanol	Kerosene	Weighting
LNG	1.00	1.00	3.00	9.00	9.00	9.00	9.00	0.344
LPG	1.00	1.00	3.00	9.00	9.00	9.00	9.00	0.344
Ammonia	0.33	0.33	1.00	6.00	6.00	6.00	7.00	0.174
Hydrogen	0.11	0.11	0.17	1.00	1.00	1.00	1.00	0.035
Ethanol	0.11	0.11	0.17	1.00	1.00	1.00	1.00	0.035
Methanol	0.11	0.11	0.17	1.00	1.00	1.00	1.00	0.035
Kerosene	0.11	0.11	0.14	1.00	1.00	1.00	1.00	0.034

λ_{max} = 7.133, CI = 0.022, CR = 0.016< 0.1

The fuel cost weightings of alternative fuels are calculated according to the pair-wise comparison of the fuels by using fuel cost coefficients which are shown in Table 2.24. Table 3.25 includes the fuel cost weightings of alternative fuels. According to the table, LNG has the dominant weighting of 0.496 that means it has the lowest fuel cost. LPG is second and hydrogen is the third alternative fuel with 0.227 and 0.073, respectively. Methanol has the lowest weighting of 0.036 which means it has the highest fuel cost if it is used on a ship as a fuel.

Table 3.25 : The fuel cost weightings of the alternative fuels.

Alternative	LNG	LPG	Hydrogen	Kerosene	Ethanol	Ammonia	Methanol	Weighting
LNG	1.00	4.00	7.00	8.00	8.00	9.00	9.00	0.496
LPG	0.25	1.00	4.00	4.00	5.00	5.00	6.00	0.227
Hydrogen	0.14	0.25	1.00	1.00	1.00	2.00	3.00	0.073
Kerosene	0.13	0.25	1.00	1.00	1.00	1.00	2.00	0.061
Ethanol	0.13	0.20	1.00	1.00	1.00	1.00	2.00	0.059
Ammonia	0.11	0.20	0.50	1.00	1.00	1.00	1.00	0.048
Methanol	0.11	0.17	0.33	0.50	0.50	1.00	1.00	0.036

λ_{max} = 7.247, CI = 0.041, CR = 0.031< 0.1

The economy performance weightings of the alternative fuels are calculated by using equation (3.6) and weightings in Table 3.26.

$$\mathbf{W_{E_i}} = \left(\mathbf{w_{i_{j1}} x\, w_{e_{j1}}}\right) + \left(\mathbf{w_{i_{j2}} x\, w_{e_{j2}}}\right) + \left(\mathbf{w_{i_{j3}} x\, w_{e_{j3}}}\right) + \left(\mathbf{w_{i_{j4}} x\, w_{e_{j4}}}\right) \tag{3.6}$$

Where W_{E_i} is the economy performance weighting of i type of alternative fuel, $w_{i_{j1}}$, $w_{i_{j2}}$, $w_{i_{j3}}$, and $w_{i_{j4}}$ are the weightings of i type of alternative fuel at j1, j2, j3, and j4 evaluation sub-criterion of the economy criterion, $w_{e_{j1}}$, $w_{e_{j2}}$, $w_{e_{j3}}$, and $w_{e_{j4}}$ are the weightings of the evaluation sub-criteria. Table 3.26 shows the economy performance weightings of each alternative fuels. It is observed that LNG has the highest weighting of 0.415, LPG has the second-highest weighting of 0.233, and kerosene has the third-highest weighting of 0.088.

Table 3.26 : The economy performance weightings of the alternative fuels.

Alternative Fuels	Commercial Effect (0.105)	Investment Cost (0.061)	Maintenance Cost (0.105)	Fuel Cost (0.729)	Weighting
Ammonia	0.040	0.431	0.174	0.048	0.084
Ethanol	0.169	0.237	0.035	0.059	0.079
Hydrogen	0.022	0.029	0.035	0.073	0.061
Kerosene	0.350	0.048	0.034	0.061	0.088
LNG	0.140	0.046	0.344	0.496	0.415
LPG	0.201	0.162	0.344	0.227	0.233
Methanol	0.079	0.047	0.035	0.036	0.041

3.3.6 The ecology weightings of the alternative fuels

The ecology weightings of the alternative fuels are calculated by considering air pollution and sea pollution effects of the alternative fuels and it was explained in detail in section 2.3.1.6. The calculation process can be followed by Table A59 to A61 in Appendices.

Table 3.27 shows the ecology performance weightings of alternative fuels. It can be seen from the table that LNG has the dominant weighting of 0.359. Hydrogen and methanol follow it with 0.241 and 0.161, respectively. These alternative fuels have lower ecological damage than the remaining alternative fuels in this study. Kerosene has the least weighting of 0.21 which means it gives the highest damage to the ecology and does not preferable fuel when it is compared with the other ones.

Table 3.27 : The ecology performance weightings of the alternative fuels.

Alternative	LNG	Hydrogen	Methanol	Ethanol	Ammonia	LPG	Kerosene	Weighting
LNG	1.00	2.00	3.00	4.00	6.00	6.00	9.00	0.359
Hydrogen	0.50	1.00	2.00	3.00	4.00	5.00	8.00	0.241
Methanol	0.33	0.50	1.00	2.00	3.00	4.00	7.00	0.161
Ethanol	0.25	0.33	0.50	1.00	2.00	3.00	6.00	0.106
Ammonia	0.17	0.25	0.33	0.50	1.00	1.00	4.00	0.060
LPG	0.17	0.20	0.25	0.33	1.00	1.00	4.00	0.052
Kerosene	0.11	0.13	0.14	0.17	0.25	0.25	1.00	0.021

$\lambda_{max} = 7.222$, CI = 0.037, CR = 0.027< 0.1

3.4 Total Performance Weightings of the Alternative Fuels

Comparison of the alternative fuels at safety, legislation, reliability, technical, economy, and ecology criteria was done to assess the total performance of the alternative fuels for shipboard usage. Each alternative fuel has the strong and weak sides. The total performance weighting table, Table 3.28, is formed to show alternative fuel weightings for each criterion and total performance of the alternative fuels to find the most suitable ones for the shipboard usage as a fuel. Equation (3.7) is used to calculate the total performance weightings of alternative fuels.

$$\mathbf{W_{TP}} = \left(\mathbf{W_{S_i} x\, W_{C_S}}\right) + \left(\mathbf{W_{L_i} x\, W_{C_L}}\right) + \left(\mathbf{W_{R_i} x\, W_{C_R}}\right) + \left(\mathbf{W_{T_i} x\, W_{C_T}}\right) + \left(\mathbf{W_{E_i} x\, W_{C_E}}\right) + \left(\mathbf{W_{EC_i} x\, W_{C_{EC}}}\right) \tag{3.7}$$

Where W_{S_i} is the safety performance weighting of i type of alternative fuel, W_{L_i} is the legislation performance weighting of i type of alternative fuel, W_{R_i} is the reliability performance weighting of i type of alternative fuel, W_{T_i} is the technical performance weighting of i type of alternative fuel, W_{E_i} is the economy performance weighting of i type of alternative fuel, W_{EC_i} is the ecology performance weighting of i type of alternative fuel, W_{C_S} is the weighting of the safety criteria, W_{C_L} is the weighting of the legislation criteria, W_{C_R} is the weighting of the reliability criteria, W_{C_T} is the weighting of the technical criteria, W_{C_E} is the weighting of the economy criteria, and $W_{C_{EC}}$ is the weighting of the ecology criteria.

According to the total performance weighting calculations, LNG has the highest weighting of 0.234. It means LNG is the most suitable alternative fuel for shipboard usage as a fuel. Methanol is the second most suitable alternative fuel for shipboard usage with the weighting of 0.151, and ammonia is the third most suitable alternative fuel with the weighting of 0.148. It can be seen from the table that kerosene is the least suitable alternative fuel for the shipboard usage with the weighting of 0.065.

3.5 Discussion about the Assessment of the Alternative Fuels

In the third section of the thesis study, possible alternative fuels were selected for this study according to their study numbers in the literature. Ammonia, ethanol, hydrogen, kerosene, LNG, LPG, and methanol were used in this study. An assessment model was formed to evaluate the performance of the selected alternative fuels for shipboard usage. The analytic hierarchy process tool was used to evaluate alternative fuels. The evaluation criteria were safety, legislation, reliability, technical, economy, and ecology.

The weightings of these criteria and their sub-criterion were found by the expert opinions, while the weightings of the alternative fuels for each criterion were found by evaluating their properties and requirements for using on a ship.

The results of the study showed that LNG has the highest total performance weighting which means it is the most suitable alternative fuel for using on a ship. Methanol is the second alternative fuel for shipboard usage. Methanol is the main focus point of this thesis study, and the assessment model showed that methanol can be considered as an alternative fuel for shipboard usage. Methanol has good safety performance, high legislation performance, high reliability performance, and good ecology performance. The technical and economy performance of the methanol was low, but it did not affect the total performance weighting of the methanol too much. Methanol showed promising results according to the conclusion of the total performance weighting.

The assessment model showed parallel results with the recent alternative fuel developments in the maritime industry. Nowadays, LNG is the most popular alternative fuel in the maritime industry, and methanol is one of the promising alternative fuels for ships. Methanol has been used as a fuel cell fuel on ships for many years at various types of fuel cells (Inal and Deniz, 2018). On the other side, the methanol fuelled commercial ships increase in number. The surprise of the assessment model is ammonia since the researchers have lost their attention and there are not too many up to date studies in the literature. But, nowadays, MAN has been working on ammonia to use it on their marine engines (Laursen, 2018). In addition to this, ammonia has been used in SCR systems as a NO_X abatement technology for many years. Urea in the SCR system reacts in the catalyst and changed into ammonia (Url 33). The maritime sector is familiar with ammonia, and it can be one of the alternative fuels if the maritime industry studies will focus on ammonia as a ship fuel. The remaining ordering of the alternative fuels was hydrogen, ethanol, LPG, and kerosene. This study shows that the assessment model matches the sector reality.

Table 3.28 : The total performance weightings of the alternative fuels.

Alternative Fuels	Safety (0.346)	Legislation (0.146)	Reliability (0.090)	Technical (0.025)	Economy (0.046)	Ecology (0.346)	Total Performance Weighting
Ammonia	0.255	0.190	0.036	0.219	0.084	0.060	0.148
Ethanol	0.200	0.190	0.048	0.040	0.079	0.106	0.143
Hydrogen	0.077	0.190	0.048	0.040	0.061	0.241	0.146
Kerosene	0.095	0.023	0.139	0.025	0.088	0.021	0.065
LNG	0.097	0.194	0.258	0.318	0.415	0.359	0.234
LPG	0.177	0.022	0.144	0.318	0.233	0.052	0.112
Methanol	0.100	0.190	0.327	0.040	0.041	0.161	0.151

4. EXPERIMENTAL STUDY WITH THE METHANOL FUEL

In the fourth section of the thesis study, the experimental preparations and the experimental findings with the methanol fuel is discussed. Firstly, the link between the experimental studies and the assessment model in the third section of the thesis study and the reasons to select methanol fuel instead of other suitable alternative fuels, which was found by the assessment model, should be explained.

The first part, third section, of the thesis study was to form an assessment model to evaluate alternative fuels for shipboard usage as a fuel. Various criteria, including safety, legislation, reliability, technical, economy, and ecology, were used to evaluate their performance. According to the results of the assessment model, LNG, methanol, and ammonia are the top three alternative fuels for shipboard usage. However it can be easy to select directly an alternative fuel for the experimental study, the assessment model was constituted to prove that the selected alternative fuel for the experimental study is suitable for the shipboard usage. This gives information to the readers that the used alternative fuel in the experimental part of the thesis study can be applied to the ships and is not far away from the real application (commercial application) possibility. The assessment model results are in parallel with commercial applications worldwide. There are commercial applications on the ships with the LNG and methanol fuels. The surprising alternative fuel is ammonia which has not been paid attention by the researchers. The reason can be higher production capability, higher applicability possibility, and lower downsides of the other alternative fuels.

Another issue is which alternative fuel from the results of the assessment model will be selected for the experimental studies. LNG is the first possible alternative fuel and it got the highest total performance weighting from the assessment model. Although it is the first alternative fuel, there are many experimental studies in the literature with the LNG fuel. It is a proven alternative fuel and there are 116 LNG fuelled commercial ships in operation and 112 confirmed new buildings (DNV GL, 2017; Zincir and Deniz, 2018b). To make an experimental study with the LNG fuel will not give new results and only verify the previous studies. In addition to this, it is hard to do an experiment with gaseous fuel. High safety level and special test equipment are needed for the experiments. For this reason, LNG was not selected as the alternative fuel for the experimental studies.

The third suitable alternative fuel by the results of the assessment model is ammonia. The studies with ammonia in the literature are generally old dated. The studies are not up to date, and it can be an opportunity to do an experimental study with ammonia to fill the gap in the literature. On the other hand, it has downsides such as high auto-ignition temperature, high toxicity, special experimental setup requirements, and lack of attention to ammonia. As a consequence, ammonia was not selected as the alternative fuel for the experimental studies.

The second alternative fuel by the results of the assessment model is methanol. The methanol fuel takes the attention of the researchers in recent years. There are various projects, most of them are in the Scandinavian region, for instance, Effship, Spireth, Methaship, Leanships, Summeth, and Greenpilot (Ellis, 2017). In addition to this, there are two methanol fuelled ships in operation and six ships are in order (Zincir and Deniz, 2018b). It can be seen that this is a transition period for the methanol fuel and it can be a good opportunity to do an experimental study with methanol and include in the literature. Also, methanol is liquid at standard temperature and pressure, less toxic than ammonia, which is almost equal to gasoline and diesel (Verhelst et al., 2019), and less safety level and special test equipment are needed for the experimental study. As a consequence of these, the methanol fuel was selected as the alternative fuel for the experimental studies.

4.1 Properties of Methanol

The production of methanol can be from fossil fuel sources or renewable sources. Natural gas and coal are common fossil fuels for methanol production (Zincir et al., 2019b). It can also be produced from wood, agricultural and municipal waste (Yao et al., 2017). Methanol can be produced from using electricity from renewable energies and carbon capture from the atmosphere or waste CO_2. This type of methanol is called as electrofuel (Verhelst et al., 2019). Methanol is one of the top five most traded chemicals worldwide (ICIS, 2017), and 20 million tons of methanol has been produced yearly as a fuel or fuel blend (Landälv, 2017).

Methanol is toxic and deadly for humans and animals, but it can easily biodegrade and dissolve in the water (Stocker, 2018). Methanol is the simplest alcohol which has a high H/C ratio and a single carbon atom that the combustion of it does not form particulate matter is the product of the combustion of long-chain hydrocarbons (Verhelst et al., 2019). Also, methanol molecules include one oxygen atom. The oxygen atom in the molecule promotes more efficient combustion. It lowers the greenhouse gases (Shahhosseini et al., 2018), and no SO_X and soot emissions are emitted. The NO_X emission is reduced by the low-temperature combustion of methanol (Pan et al., 2015; Gong et al., 2018). In addition to the positive effect of the oxygen atom in the methanol molecule on the emissions, methanol requires lesser air which results in a low stoichiometric air/fuel ratio (Verhelst et al., 2019).

Methanol has a high latent heat of vaporization that forms a charge cooling effect in the cylinder. It results in lower heat transfer loss, lower compression work, higher engine efficiency (Shamun et al., 2018; Zincir et al., 2019a). Also, the cooling effect increases the intake air density and volumetric efficiency (Verhelst et al., 2019).

Higher engine efficiencies can be obtained by the high latent heat of vaporization, fast-burning velocity, high knock-resistance, and zero carbon-to-carbon bonds of methanol that allows engine technology developments, for instance, increased compression ratios, downsizing, and dilution, etc (Verhelst et al., 2019).

The physical properties of methanol are almost similar to other marine fuels and can be stored at the same bunker tanks for conventional fuels after minor modifications (Stocker, 2018). Also, it can be combusted in diesel engines by doing minor changes and additions to the engine.

4.2 Methanol-fuelled Diesel Engine Concepts

The main combustion concepts for the internal combustion engines are compression ignition (CI) and spark ignition (SI) concepts. In addition to these combustion concepts, there is another combustion concept is named as homogeneous charge compression ignition (HCCI). Some combustion concepts are between these three fundamental combustion concepts. Figure 4.1 shows the combustion concepts that are explained in the thesis study. Methanol cannot be burned in CI engines, due to its high octane rating (Zincir et al., 2019b), but various combustion concepts can burn methanol in CI engines. Dual-fuel, direct injection spark ignition (DISI), HCCI, reactivity controlled compression ignition (RCCI), and partially premixed combustion (PPC) are the combustion concepts which can use methanol as a fuel and they are explained in detail.

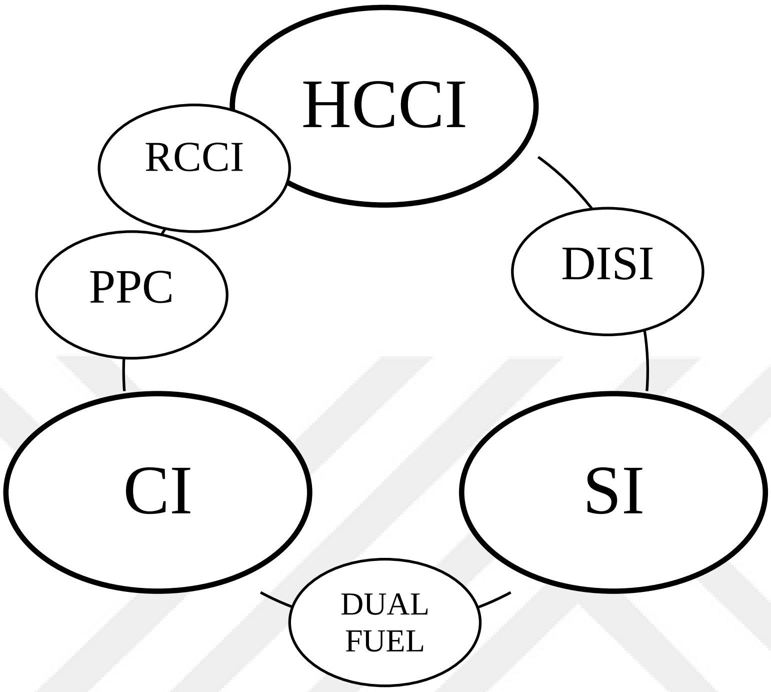

Figure 4.1 : Scheme of the combustion concepts. (Figure reproduced and adapted from Johansson, 2016.)

4.2.1 HCCI

The homogeneous charge compression ignition (HCCI) concept, one of the first low-temperature combustion concepts, is an example of kinetic combustion (Lönn, 2019). Methanol and air are a mixture before enter into the cylinder and the combustion event begins simultaneously by the role of auto-ignition (Tuner, 2016). The charge in the cylinder is diluted to keep the reactivity moderately to prevent high pressure rise rate (PRR) and peak in-cylinder pressure during the combustion event happens in various zones of the combustion chamber (Johansson, 2016). HCCI concept provides high efficiency, low NO_X, and soot emissions at the same time. On the other hand, it has disadvantages of difficulties in the combustion control, low power production range, and high PRR (Zincir et al., 2019a). High total hydrocarbon (THC) and CO emissions are other disadvantages of HCCI, due to the remained unburned fuel-air mixture in the crevice volume (Lönn, 2019).

4.2.2 Dual fuel concept

Dual fuel engines use two different fuels. One fuel has a higher cetane number than the other fuel. A high cetane fuel, diesel, is injected into the cylinder directly as pilot fuel and ignited by the high pressure and temperature during the compression, and then it ignites the main fuel, methanol (Tuner, 2016). The main fuel can be injected into the port or directly injected into the cylinder in different applications. The timing of the combustion event is determined by the diesel spray, and the premixed charge of methanol-air is burned with flame propagation the same as SI engines (Johansson, 2016).

4.2.3 DISI

Direct injection spark ignition (DISI) combustion is a concept between SI and HCCI. A spark plug is used to start the combustion of high octane fuels, such as methanol, in diesel engines. The combustion event is started with a flame propagation the same as SI engines and concludes with HCCI type combustion (Johansson, 2016). Negative valve overlaps are often used to hold residual gases in the combustion chamber to heat the combustion mixture, and then the mixture is ignited by the spark plug (Li, 2018).

4.2.4 RCCI

Reactivity controlled compression ignition (RCCI) is a similar concept to the dual-fuel concept. A fuel with a high octane rating is premixed with air while another fuel with a low octane rating is injected into the cylinder directly. The only difference from the dual-fuel concept is the in-cylinder charge is diluted and low-temperature combustion is commenced as same as HCCI (Tuner, 2016). The concept uses fuels with different auto-ignition characteristics to control ignition and combustion (Lönn, 2019). The high fuel efficiency of 60% was achieved with the RCCI concept (Splitter et al., 2013).

4.2.5 PPC

Partially premixed combustion (PPC) is an intermediate process of the compression ignition concept and HCCI concept (Zincir et al., 2019b). All the injected fuel is in the cylinder at the ignition event. It means the start of combustion (SOC) and end of injection (EOI) are separated (Tuner, 2016). The combustion event happens in a stratified charge, but it is not diffusion-controlled, spray-driven combustion (Johansson, 2016). The PPC concept comes with easy combustion control, low NO_X and soot levels, and high engine efficiency (Zincir et al., 2019a). The partially premixed charge has a high burning rate which can reduce the heat transfer losses and reduce the NO_X emissions due to a shorter high-temperature period during the combustion event (Shamun, 2019).

4.3 Reasons to Select PPC Concept for the Experimental Studies

The reasons to select PPC concept are listed below:

- Lesser modification need on the engine and the related systems
- Possibility of the high engine efficiency
- Low NO_X and PM emissions
- One of the recent combustion concepts which can fill the gap in the literature
- Possibility of the application of the PPC concept on a marine engine

4.4 Literature Review about the PPC Concept

The history of the PPC studies was started with a low compression ratio and a high exhaust gas recirculation (EGR) at a stoichiometric engine operation. Recent studies have used high-octane fuels, such as gasoline or alcohols (Kaiadi et al., 2013). It is aimed to separate the end of injection and start of the combustion by these applications.

There are various studies with different fuels and engine load ranges in the literature. A study was performed with four fuels in the gasoline boiling range and diesel MK1 (Solaka et al., 2012). They investigated the low load performance of these fuels. The engine was operated between the ranges of 2 bar and 8 bar indicated mean effective pressure (IMEP) at 1500 rpm. They found that the diesel MK1 can be operated under 3 bar IMEP while others can be operated at 2 bar IMEP.

Han et al. (2017) performed a study with PPC by using n-butanol at 6 bar IMEP. They wanted to investigate the advantages and challenges of using neat n-butanol in a diesel engine. They achieved 45.3% indicated thermal efficiency with n-butanol while it was 45.4% for diesel.

The combustion efficiency was slightly lower due to the lower reactivity of n-butanol. It was also observed that NO_X emission was lower and almost zero smoke emission was emitted with n-butanol.

Another study was about the low load limitations of high-octane fuels by considering intake temperature sweep (Wang et al., 2017). They used primary reference fuels (PRF) which have octane numbers of 70, 80, and 90 on a diesel engine under 5 bar IMEP as low load and 2.5 bar IMEP as the idle load at 1200 rpm. They observed that a higher intake temperature provides more stable and complete combustion.

Belgiorno et al. (2018), made a gasoline PPC study under 3, 6, and 9 bar brake mean effective pressure (BMEP) at 1500 rpm to observe the effect of engine calibration parameters and the combination of them on the engine performance and emissions. They aimed to reach high engine efficiency and low emissions. The results of their study showed that the gasoline PPC had 2% higher engine efficiency, lower soot and 0.5 g/kWh lower NO_X emissions than the diesel combustion. There is another study investigated the engine calibration parameters on engine performance and emissions (Yin et al., 2019a). The fuel was the mixture of 80% Swedish 95 octane gasoline and 20% n-heptane and the engine was operated at 5, 11, 14 bar IMEP. They achieved 51.5% gross indicated efficiency (η_{GIE}) and 48.7% net indicated efficiency (η_{NIE}) at stable operating conditions. They also got 47.5% average η_{NIE} during the transient condition. They noted that NO_X, CO, and THC emission complied with the Euro VI limits.

A study by An et al. (2019) investigated the effect of the intake temperature on the combustion stability of the PPC operation. PRF77 was used as a fuel at the experiments. They noticed that the in-cylinder temperature and IMEP were reduced, the combustion phasing was retarded, and the combustion stratification was increased by the lower intake temperature.

Yin et al. (2019b), had another PPC study which focused on improving the engine efficiency by the multiple injections. PRF87 was used as an experiment fuel. They observed that when they used multiple injections, the engine efficiency was reached 48%.

Methanol is one of the suitable fuels for the PPC concept. Shamun et al. (2018) investigated the charge cooling effect of methanol fuel. They found that the latent heat of vaporization of methanol cooled down the cylinder and reduced the compression work. Moreover, the charge cooling effect of methanol reduced the heat transfer loss, increased engine efficiency, and minimized the NO_X emission during the PPC operation. Shamun (2019) has another PPC study with various alternative fuels including methanol. He did experiments on a heavy-duty and light-duty engines to experience the methanol PPC operation. The findings of the study were the use of methanol can reduce the net well-to-wheel CO_2 emissions and increasing efficiency. The PM emissions were almost zero at the experiments during methanol PPC operation. Methanol has high latent heat of vaporization and laminar flame speed that provides low-temperature combustion and reduces the heat transfer losses which results in increased thermal and gross indicated efficiencies. The NO_X emission is lower than the CI concept, but CO and THC emissions are higher at low loads, due to the crevice losses and cooler combustion event.

Lönn (2019), made a study with a metal engine and optical engine to observe the PPC combustion behavior of methanol. The combustion of methanol was visualized by the high-speed cameras. It was noticed that methanol was burned fast and the methanol spray boundaries were not clearly defined. The combustion event was almost homogenous in the cylinder. The single and multiple injection strategies were also investigated to observe the effects of high latent heat of vaporization. It was noted that a big separation between the multiple injections can reduce the cooling effect of methanol in the cylinder.

A previous study investigated the effects of intake temperature on low load limitations of methanol PPC (Zincir et al., 2019a). The engine was operated under 3 bar IMEP as the low load with the varying intake temperature between 102°C and 107°C and 1 bar IMEP as the idle load with the varying intake temperature between 108°C and 151°C at 800 rpm. The engine stability, the combustion characteristics, and emissions of methanol PPC were observed. Additionally, the combustion phasing sweep was done at 1 bar IMEP and a constant intake temperature of 130°C. The findings of the study are a higher intake temperature was needed to maintain the same engine stability at lower engine loads with the single injection case, and the split injection case needed lower intake temperature than the single injection case. The combustion efficiency raised from 96% to 99%, and the thermodynamic efficiency remained constant at 43% at 3 bar IMEP, while the combustion efficiency was around 98-99% and the thermodynamic efficiency varied from 24% to 30% at 1 bar IMEP under the single injection and the split injection cases. The CO emissions were constant with the change of the intake temperature, but the THC emissions reduced with a higher intake temperature. The NO_X emissions remained constant or increased with a higher intake temperature in different cases.

Another study was about the investigation of the environmental, operational, and economic performance of methanol PPC at the slow speed operation of a marine engine (Zincir et al., 2019b). The main purpose of the study was to reduce the emitted shipping emissions to the coastal settlements while do not raise the risk and expense of the engine operation. The study investigated the engine emissions, combustion properties of the methanol PPC, engine efficiency, specific fuel consumption, and fuel cost by also comparing with marine gas oil (MGO). According to the comparison with MGO, methanol PPC had lower CO_2 emissions and NO_X emissions were in the limits of IMO NO_X Tier III. The methanol PPC had zero SO_X and PM emissions. It was observed that methanol PPC has not got any combustion issues at the low load operation. The methanol PPC had the combustion efficiency of between 94% and 99%, the thermodynamic efficiency of between 45% and 47% and the gross indicated efficiency of between 42% and 46%, while the MGO had the gross indicated efficiency of 24% and 32%. The fuel cost comparison showed that methanol is competitive with the low sulfur MGO.

4.5 Motivation of the Experimental Studies

The motivation of investigating the effects of methanol in the CI engine under the partially premixed combustion concept is the unique combustion properties of methanol which result in reduced CO_2 and NO_X emissions, close to zero PM emissions and zero SO_X emission. Furthermore, the high latent heat of vaporization of methanol can increase engine efficiency by reducing compression work. Also, partially premixed combustion has the potential to decrease CO_2 emission by the increased engine efficiency and mitigate NO_X and PM emissions at the same time due to the properties of the combustion concept. The experimental studies of the thesis study investigate the methanol PPC concept which can be a possible solution for the shipboard emissions and can comply with the IMO emission limits if it is applied on a ship.

The experimental studies are focused on engine efficiency, specific fuel consumption, and emissions, but not limited to these investigations. The engine stability, ignitability, and the combustion characteristics are also investigated by also considering the intake temperature and start of injection (SOI) timing to find out that the methanol PPC can be applied on a ship or cannot.

4.6 Laboratory and Test Rig

The experimental studies of the thesis study were performed at the laboratory of the Division of Combustion Engines, Department of Energy Sciences at Lund University, Sweden. The laboratory includes 13 engine test cells and 15 engine test rigs. Each test rig has a dynamometer, engine hardware, control system, and connection to emission analyzers. There are Volvo and Scania engines, and one Wartsila engine. Four of these engines are the light-duty engines, one of them is a CFR engine for the fuel research, and the remaining are the heavy-duty engines. There are also six optical engines in the laboratory (Url 34).

The experimental studies were done on a six-cylinder Scania D13 heavy-duty engine modified to run on only one cylinder. A new heavier flywheel was mounted, the pistons were replaced with hollow weights to balance the working of the engine and de-activating the compression (Shamun, 2019). The engine specifications are shown in Table 4.1.

Table 4.1 : Engine specifications.

Engine Specifications	
V_d	2124 cm^3
Stroke	160 mm
Bore	130 mm
r_c	17.3:1
Swirl ratio	2:1
IVC	-141°CA ATDC
EVO	137°CA ATDC
Umbrella angle	148°
Injector type	12-hole MeOH injector

Instead of measuring the engine torque, the engine was coupled with an electric motor and it was controlled by a frequency converter. As a result, the engine load was calculated by the in-cylinder pressure gathered by the in-cylinder pressure sensor and the charge amplifier.

Figure 4.2 shows the picture of the engine and Figure 4.3 shows the experimental setup diagram. The test engine did not have a turbocharger, for this reason, the pressurized air was delivered from an external compressor and the turbocharger back-pressure was simulated by the butterfly back-pressure valve. The intake air was heated by the 7.5 kW air heater for increasing the ignitability of the methanol. Also, there was an exhaust gas recirculation (EGR) line with EGR plenum and EGR cooler that EGR valve was used to deliver some of the exhaust to the EGR line, but EGR was not used in the thesis study.

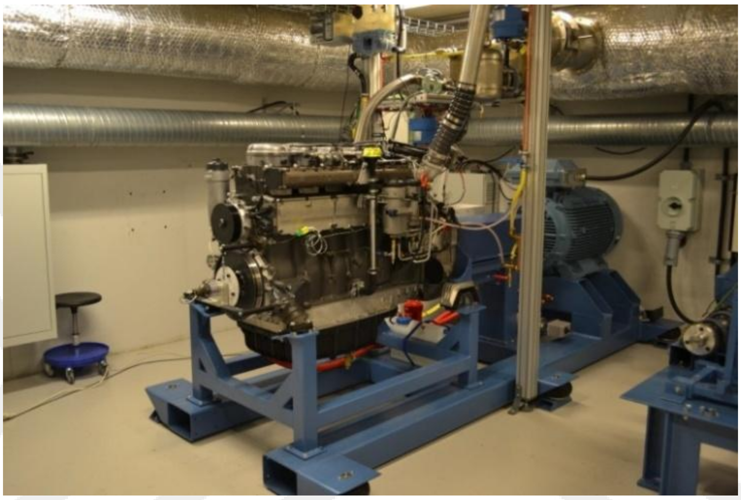

Figure 4.2 : Picture of the engine.

The crank position was measured by the crank angle encoder located on the crankshaft. A disk on the crankshaft rotates and an output signal was generated at every 0.2°CA by photoelectric scanning technique.

There were pressure sensors in the intake, exhaust and inside the cylinder head, and thermocouples were placed at the intake and exhaust manifolds. Additionally, there were some other pressure sensors and thermocouples to maintain the safe operation of the engine. Table 4.2 shows the specifications of the sensors used in the engine test cell.

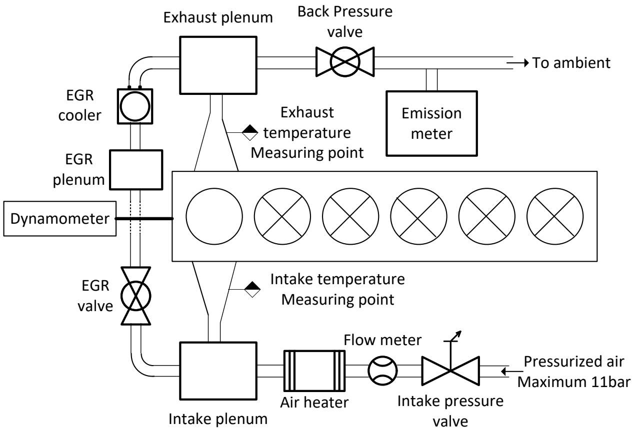

Figure 4.3 : Experimental setup diagram.

The fuel system of the experimental setup was a common rail system which was modified for the single-cylinder operation. The high-pressure fuel pump, controlled by a solenoid valve, was adjusted to operate with methanol by changing its gaskets, materials, and fuel flow rate. The fuel injector was also compatible with the methanol corrosivity by the modification and the fuel flow rate was higher than the regular diesel fuel injector (Shamun, 2019).

Table 4.2 : Specifications of the sensors in the test cell.

Sensor	Model	Measurement Range	Precision
CA Encoder	Kistler 2614CK	0-12000 rpm	±0.03°CA
Cylinder Pressure	Kistler 7061B Kistler 5011	0-250 bar	
Intake Manifold Pressure	Kistler 4075A 10	0-10 bar	±0.03% FS
Exhaust Manifold Pressure	Kistler 4075A 10	0-10 bar	±0.03% FS
Fuel Injection Pressure	Kistler 4067C	0-3000 bar	±0.5% FS
Air Flow Meter	MicroMotion 1700	0-725 kg/min	±0.1% FS
Fuel Flow Meter	Vettek APP 25.R2	0-25000 gr	±0.1 gr
O_2	ETAS ES630.1	0-25%	
CO		0-10000 ppm	±1% FS
NO_X	Horiba	0-1000 ppm	±1% FS
THC	MEXA7500DEGR	0-4000 ppm	±1% FS
O_2		0-25%	±1% FS

The exhaust emissions were measured by Horiba MEXA 7500DEGR, after the exhaust gases were sampled through a heated line, where the condensation of the gases was avoided by the maintained temperature above 190°C (Zincir et al., 2019a). The CO emission was measured by an infrared detector method while the NO_X and NO emissions were measured by the chemiluminescence detector and the THC emission was measured by flame ionization detector. The SO_X emission was not measured due to the sulfur-free structure of methanol, and the PM emission was not investigated, due to the low emission amount encountered (Shamun et al., 2017a).

The chemical-grade methanol which had a purity of 99.85% was used in the experiments. Water and trace amounts of organic compounds constituted the remaining content. Table 4.3 shows the properties of methanol. Methanol reduces the lubricity, due to its sulfur-free content and low viscosity. 200 ppm of Infineum R655 was used as an additive to improve the lubricity in the fuel system. The energy density of the additive was neglected.

The experimental setup was constituted by the test engine, real-time target PC for forming the connection between host PC and the test engine, data logger for recording engine parameters, host PC to control the engine, and emission PC to make the connection between the emission analyzer and the host PC. Figure 4.4 shows the general layout of the experimental setup. The measurements were obtained and the engine was controlled by National Instruments LabView software. The injection timing, injection duration, rail pressure, intake pressure, back-pressure, the position of the coolant valves, and heating of the intake air can be easily done via the software. Moreover, the engine combustion parameters, emissions and operating parameters of the engine can be observed at the software interface. Only, the engine speed was controlled by a separate controller of the electric motor and frequency converter.

Table 4.3 : Properties of methanol (Zincir et al., 2019a; Zincir et al., 2019b).

Properties of methanol	
RON	107-109
MON	92
H/C	4
O/C	1
LHV (MJ/kg)	19.9
A/F_S	6.45
Density (kg/m^3)	792
Heat of vaporization (kJ/kg)	1103

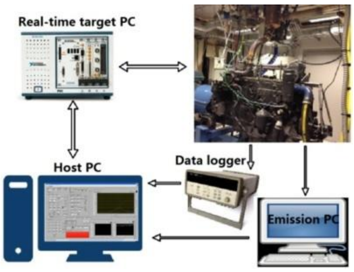

Figure 4.4 : General layout of the experimental setup (Shen, 2016).

4.7 Data Post Processing

The data post-processing was done by using Matlab codes which were prepared by the Ph.D. students of Division of Combustion Engines, Department of Energy Sciences, Lund University. There were Matlab codes for the light-duty or heavy-duty and single cylinder or multi-cylinder engines. The Matlab codes for single cylinder heavy-duty engines which were modified for the Scania D13 engine was used in the thesis study. The main codes for the post process were mean effective pressure and efficiencies, heat release rate, and exhaust emissions. The references benefited from were Heywood (1988), Johansson (2006), Lönn (2019), and Shamun (2019) for this section of the thesis study.

Since the test engine was modified to work as the single-cylinder, the produced torque, BMEP or brake efficiency could not be measured. For this reason, the energy flow from fuel chemical energy to the produced energy was expressed in mean effective pressure. This can provide a comparison between different engines because the energy is normalized with the engine displacement. Figure 4.5 shows the flowchart for the mean effective pressures.

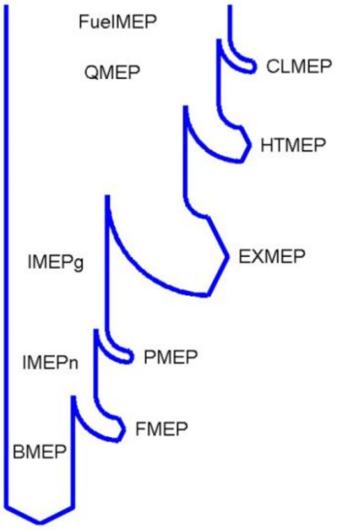

Figure 4.5 : Mean effective pressure flowchart (Shamun, 2019).

First term in the flowchart is fuel indicated mean effective pressure (FuelMEP). It is indicated as:

$$\mathbf{FuelMEP} = \frac{m_f \text{ x } Q_{LHV}}{V_D} = \frac{\dot{m}_f \text{ x } n_T \text{ X } Q_{LHV}}{N \text{ X } V_D} \qquad (4.1)$$

where $\dot{m}_f$ is the fuel flow, n_T is the stroke factor, Q_{LHV} is the lower heating value of the fuel, N is the engine speed, and V_D is the engine displacement. The fuel delivered to the engine cannot be burned completely and the output energy from the combustion event is lower than the fuel chemical energy. The energy of the combustion event is indicated as:

$$\mathbf{QMEP} = \mathbf{FuelMEP\ x}\ \eta_{\mathbf{c}} \tag{4.2}$$

where η_c is the combustion efficiency which will be explained further.

The third term in the flowchart is gross indicated mean effective pressure ($IMEP_g$) which was calculated by gathering in-cylinder pressures. This term includes the calculations at the compression and expansion events. Net indicated mean effective pressure ($IMEP_n$) includes the whole cycle.

$$\mathbf{IMEP_g} = \frac{\mathbf{1}}{\mathbf{V_D}}\int_{\mathbf{-180}}^{\mathbf{180}} \mathbf{PdV} \tag{4.3}$$

$$\mathbf{IMEP_n} = \frac{\mathbf{1}}{\mathbf{V_D}}\int_{\mathbf{-360}}^{\mathbf{360}} \mathbf{PdV} \tag{4.4}$$

where P is the pressure vector and V is the volume vector.

Three efficiencies are taken into consideration in the thesis study. These are the combustion efficiency (η_c), the thermodynamic efficiency (η_t), and the gross indicated efficiency (η_{GIE}). They are impressed with equation (4.5) to (4.7).

$$\eta_{\mathbf{c}} = \frac{\sum \frac{\mathbf{M_i}}{\mathbf{M_p}} \mathbf{X_i^*}\left(\mathbf{1}-\mathbf{X_{H_2O}}\right)\mathbf{Q_{LHV,i}}}{\frac{\mathbf{Q_{LHV,f}}}{\mathbf{1+A/F}}} \tag{4.5}$$

where M_i is the molar mass of i type of the exhaust gas, M_p is the molar mass of all emissions, X_i^* is the dry exhaust gas fraction, X_{H_2O} is the water fraction, $Q_{LHV,i}$ is the lower heating value for each exhaust gas, $Q_{LHV,f}$ is the lower heating value for the fuel, A/F is the air to fuel ratio. Equation (4.5) is used for i= H_2, THC, CO, and sometimes for PM.

$$\eta_{\mathbf{t}} = \frac{\mathbf{IMEP}}{\mathbf{QMEP}} \tag{4.6}$$

$$\eta_{\mathbf{GIE}} = \frac{\mathbf{IMEP}}{\mathbf{FuelMEP}} \tag{4.7}$$

The heat release rate code is constituted by the application of the first law of thermodynamics by assuming that the combustion chamber is a closed system.

$$\frac{\mathbf{dQ}}{\mathbf{dt}} = \frac{\mathbf{dU}}{\mathbf{dt}} + \frac{\mathbf{dW}}{\mathbf{dt}} + \frac{\mathbf{dQ_{HT}}}{\mathbf{dt}} + \frac{\mathbf{dQ_{Crevice}}}{\mathbf{dt}} + \frac{\mathbf{dQ_{Blowby}}}{\mathbf{dt}} \tag{4.8}$$

where $\frac{dQ}{dt}$ is the heat released from the combustion event, $\frac{dU}{dt}$ is the internal energy, $\frac{dW}{dt}$ is the work done by the piston, $\frac{dQ_{HT}}{dt}$ is the heat transfer to the cylinder walls, $\frac{dQ_{Crevice}}{dt}$ is the heat loss from the crevice volumes, and $\frac{dQ_{Blowby}}{dt}$ is the heat loss by the blowby. $\frac{dQ_{Crevice}}{dt}$ and $\frac{dQ_{Blowby}}{dt}$ are assumed as zero in the thesis study.

The internal energy of the system, U, is indicated as:

$$\mathbf{U = m \ x \ C_v \ x \ T} \tag{4.9}$$

where m is the mass inside the cylinder, C_v is the specific heat of a constant volume, and T is the in-cylinder temperature. And then,

$$\frac{\mathbf{dU}}{\mathbf{dt}} = \mathbf{m \ x \ C_v \ x} \ \frac{\mathbf{dT}}{\mathbf{dt}} \tag{4.10}$$

The gas in the combustion chamber is assumed as the ideal gas. It means the in-cylinder temperature is assumed to be the same for all regions of the combustion chamber.

$$\mathbf{p \ x \ V = m \ x \ R \ x \ T} \tag{4.11}$$

where p is the in-cylinder pressure, V is the volume of the combustion chamber, m is the moles of the gas, and R is the gas constant. If the ideal gas law is differentiated and inserted into equation (4.10):

$$\frac{\mathbf{dU}}{\mathbf{dt}} = \frac{\mathbf{C_v}}{\mathbf{R}} \ \mathbf{x} \ (\mathbf{p \ x} \ \frac{\mathbf{dV}}{\mathbf{dt}} + \ \mathbf{V \ x} \frac{\mathbf{dP}}{\mathbf{dt}}) \tag{4.12}$$

The system is assumed that it is insulated and there is not any flow into or out from the cylinder. From these assumptions, $\frac{dW}{dt}$ is

$$\frac{\mathbf{dW}}{\mathbf{dt}} = \mathbf{p \ x} \ \frac{\mathbf{dV}}{\mathbf{dt}} \tag{4.13}$$

where p and V are the cylinder pressure and the cylinder volume, respectively. The specific gas constant and the specific heat ratio are expressed with equations (4.14) and (4.15), respectively. And then, they form equation (4.16).

$$\mathbf{R = C_p - C_v} \tag{4.14}$$

$$\mathbf{\Upsilon = \frac{C_p}{C_v}} \tag{4.15}$$

$$\mathbf{\frac{C_v}{C_p - C_v} = \frac{1}{\Upsilon - 1}} \tag{4.16}$$

By inserting equations (4.10), (4.13), (4.15), and (4.16) into equation (4.8), the final heat release rate expression is:

$$\mathbf{\frac{dQ}{dt} = \frac{\Upsilon}{\Upsilon - 1} p \frac{dV}{dt} + \frac{1}{\Upsilon - 1} V \frac{dP}{dt} + \frac{dQ_{HT}}{dt}} \tag{4.17}$$

To estimate $\frac{dQ_{HT}}{dt}$, heat transfer model of Woschni was used in the thesis study which is indicated in equation (4.18).

$$\mathbf{\frac{dQ_{HT}}{dt} = A_w \text{ x } h \text{ x } (T_g - T_w)} \tag{4.18}$$

where A_w is the wall areas of the combustion chamber, h is the empirical heat transfer coefficient, T_g is the gas temperature, and T_w is the wall temperature. h is indicated as:

$$\mathbf{h = C \text{ x } B^{-0.2} \text{ x } P^{0.8} \text{ x } T^{-0.55} \text{ x } w^{0.8}} \tag{4.19}$$

where C is a tunable contant, B is the cylinder bore (m), P is the mean cylinder gas pressure (kPa), T is the mean cylinder gas temperature (K), and w is the average cylinder gas velocity (m/s):

$$\mathbf{w = c_1 \text{ x } \bar{s} + c_2 \frac{V_d \text{ x } T_r}{P_r \text{ x } V_r} (P - P_m)} \tag{4.20}$$

where $\bar{s}$ is the average piston velocity, T_r is the temperature at a reference point, P_r is the pressure at a reference point, V_r is the volume at a reference point, and P_m is the motoring pressure.

The third Matlab code is about exhaust emissions. The code includes CO_2, NO_X, CO, THC, and $O_{2,p}$. It is assumed that NO_X emissions are the sum of NO and NO_2 emissions. The THC emission is assumed as $C_aH_bO_c$. The combustion event is simply expressed as:

$$\mathbf{C_aH_bO_c + \lambda \, x \, n_{O_{2,r}}(O_2 + 3.773N_2) = n_{C_aH_bO_c} \, x \, C_aH_bO_c + n_{CO_2} \, x \, CO_2 + n_{H_2O} \, x \, H_2O + n_{CO} \, x \, CO + n_{H_2} \, x \, H_2 + n_{O_{2,p}} \, x \, O_2 + n_{N_2} \, x \, N_2 + n_{NO} \, x \, NO + n_{NO_2} \, x \, NO_2} \tag{4.21}$$

where n is the number of moles and λ is air to fuel equivalence ratio. The gas concentration of each emission type i is:

$$\mathbf{X_i = \frac{n_i}{n_p}} \tag{4.22}$$

where n_i is the mole number of i type of emission and n_p is the mole number of all the products. Equation (4.21) can be re-written as:

$$\mathbf{C_aH_bO_c + \lambda \, x \, n_{O_{2,r}}(O_2 + 3.773N_2) = n_p(X_{C_aH_bO_c} \, x \, C_aH_bO_c + X_{CO_2} \, x \, CO_2 + X_{H_2O} \, x \, H_2O + X_{CO} \, x \, CO + X_{H_2} \, x \, H_2 + X_{O_2} \, x \, O_2 + X_{N_2} \, x \, N_2 + X_{NO} \, x \, NO + X_{NO_2} \, x \, NO_2)} \tag{4.23}$$

An equilibrium calculation for C, H, O, and N is done by equation (4.24) to (4.28), respectively.

$$\mathbf{a = n_p(a \, x \, X_{C_aH_bO_c} + X_{CO} + X_{CO_2})} \tag{4.24}$$

$$\mathbf{b = n_p\left(b \, x \, X_{C_aH_bO_c} + 2X_{H_2O} + 2X_{H_2}\right)} \tag{4.25}$$

$$\mathbf{c + 2\lambda n_{O_2} = n_p(c \, x \, X_{C_aH_bO_c} + 2X_{CO_2} + X_{H_2O} + X_{CO} + 2X_{O_2} + X_{NO} + 2X_{NO_2})} \tag{4.26}$$

$$\mathbf{2 \, x \, 3.773\lambda \, x \, n_{O_2} = n_p(2X_{N_2} + X_{NO} + X_{NO_2})} \tag{4.27}$$

$$\mathbf{X_{C_aH_bO_c} + X_{CO_2} + X_{H_2O} + X_{CO} + X_{H_2} + X_{O_2} + X_{N_2} + X_{NO} + X_{NO_2} = 1} \tag{4.28}$$

The exhaust gas CO and CO_2 emission fraction can be depended on H_2O and H_2. Equation (4.29) shows the relation between them.

$$\mathbf{K(T)} = \frac{\mathbf{X_{CO}\ x\ X_{H_2O}}}{\mathbf{X_{CO_2}\ x\ X_{H_2}}} \tag{4.29}$$

The combustion equilibrium is usually assumed as commenced at 1740 K that means K(T) is 3.5 (Shamun, 2019). In addition to this, the measurement method must be taken into consideration during the emission calculations, since some emissions are measured as dry while others are as wet. Equation (4.30) shows the relation between the wet measurement and dry measurement.

$$\mathbf{X_i = X_i^*(1 - X_{H_2O})} \tag{4.30}$$

where X_i is the wet and X_i^* is the dry fraction of a specy.

4.8 Engine Operating Parameters

This section gives information about the engine operating parameters during the experiments. There are various injection and intake parameters that affect the combustion event of high octane fuels such as methanol, especially at the low load PPC operation. The intake temperature is one of these parameters. The previous study showed that combustion stability is higher and the combustion event is more complete with a higher intake temperature (Zincir et al., 2019a). There are also some other supportive studies in the literature with various fuels (Maurya and Agarwal, 2011; Sarjovaara et al., 2015; Woo et al., 2016; Tang et al., 2017). Hence, the experiments were started with the low load and the intake air sweep was done at 2 bar $IMEP_g$ to observe the effect on the combustion performance and emissions of the engine. The intake air was heated up to 160°C and the sweep was done until 145°C. Table 4.4 shows the engine operating parameters in detail.

Table 4.4 : Engine operating parameters from 2 bar to 8 bar $IMEP_g$.

Engine Operating Parameters				
$IMEP_g$ [bar]	2	3	5	8
Rail pressure [bar]	400	400	1000	1200
Injection strategy [-]	Single	Single	Single	Split
Injection timing [°CA]	-18	-35 / -33 / -30 / -28	-7	-20 | -5
Injection duration [µs]	1100 - 1120	1300 – 1380	960	390 | 1040
Intake pressure [bar abs]	1	1	1.2	1.8
Intake temperature [°C]	160 / 155 / 150 / 145	145	145	145
Coolant temperature [°C]	85	85	85	85
Engine speed [rpm]	800	800	1000	1200
EGR [%]	0	0	0	0
λ	~4.3	~3.3	~2.8	~3.4

The injection timing of the fuel is another important parameter that affects the combustion event directly. The injection timing sweep was done at the experimental studies to observe the effect on combustion performance and emissions. This sweep was done at 3 bar $IMEP_g$ engine load. This engine load represents the slow speed sailing of a ship during entering the port, leaving the port or strait and canal passages. These areas contain high risk and danger and it is important to maintain the stable operation of the main engine (Zincir et al., 2019b). The injection timing sweep was done at the experiments to test and control the combustion and emissions. Table 4.4 shows the details of the engine operating parameters. The engine loads of 5 bar and 8 bar $IMEP_g$ represents the lower-medium loads of a ship. The details of the engine operating parameters are shown in Table 4.4. These loads were operated to observe the combustion performance and emissions at the medium load of the engine.

Table 4.5 shows the engine operating parameters of the engine at 10 bar $IMEP_g$ single injection case. The injection sweep was done from -7°CA to -2°CA. And Table 4.6 shows the engine operating parameters of the engine at 10 bar $IMEP_g$ split injection case. This engine load is in the range of the upper-medium load of the engine. The effect of the fuel injection parameters on the combustion performance and the emissions of the engine were investigated. The first injection sweep was done by changing the first injection from -23°CA to -17°CA while the second injection was constant at -5°CA. The second injection sweep was done by changing the second injection from -8°CA to -2°CA while the first injection was constant at -20°CA. The first injection and second injection duration proportions were changed and lastly, the rail pressure was changed from 1000 bar to 1400 bar.

Table 4.5 : Engine operating parameters at 10 bar $IMEP_g$ single injection case.

Engine Operating Parameters	
Rail pressure [bar]	1200
Injection strategy [-]	Single
Injection timing [°CA]	-7 / -5 / -2
Injection duration [μs]	1260
Intake pressure [bar abs]	2.05
Intake temperature [°C]	145
Coolant temperature [°C]	85
Engine speed [rpm]	1200
EGR [%]	0
λ	~3.1

Table 4.6 : Engine operating parameters at 10 bar IMEP$_g$ split injection case.

Engine Operating Parameters				
Rail pressure [bar]	1200	1200	1200	1000/1200/1400
Injection strategy [-]	Split	Split	Split	Split
Injection timing [°CA]	-23/-20/-17 | -5	-20 | -8/-5/-2	-20 | -5	-20 | -6/-5/-4
Injection duration [μs]	330 | 1190	330 | 1190	330/230/140 |1190/1240/1230	300/230/220 | 1350/1240/1140
Intake pressure [bar abs]	2.05	2.05	2.05	2.05
Intake temperature [°C]	145	145	145	145
Coolant temperature [°C]	85	85	85	85
Engine speed [rpm]	1200	1200	1200	1200
EGR [%]	0	0	0	0
λ	~3.1	~3.1	~3.1	~3.1

5. EXPERIMENTAL RESULTS

In this section, the experimental study findings are presented. The presented findings include discussions about the combustion properties, engine efficiency, and engine emissions under 2 bar, 3 bar, 5 bar, 8 bar, and 10 bar $IMEP_g$ engine loads.

5.1 Results Under 2 bar $IMEP_g$ Engine Load

IMO stated that the maneuvering load of a ship main engine is the load below 20% maximum continuous rating (MCR) which maintains the ship speed above 3 knots (IMO, 2014). In addition to this, the slow steaming, a fuel-saving and emission reduction approach was firstly applied by Maersk in 2007 (Zincir et al., 2019b), can be executed at the engine load of 10% MCR (Jensen and Jakobsen, 2009).

Under the light of this information, the experiments started with the possible lowest engine load. 2 bar $IMEP_g$ engine load was the lowest engine load to operate, because coefficient of variation (COV) $IMEP_n$, which is the indicator of the combustion stability, was higher than the upper limit of 5% (Przybyla et al., 2016), and the CO and HC emissions were above the limit of the measurement range of the emission analyzer and as a consequence the efficiencies were not calculated below 2 bar $IMEP_g$. This engine load is around the 10% load of the engine and it represents the deadslow sailing of a ship while entering a port, leaving a port, canal or strait passage.

Methanol has a high octane rating which means it has high resistance to the auto-ignition. To overcome this difficulty in a diesel engine during the PPC concept, the intake air is heated up to a certain level and delivered into the cylinder. In the thesis study, the intake temperature sweep was done at this engine load to observe the effect of the intake temperature on the combustion event, efficiency, and emissions of the engine.

The intake temperature change is more effective at lower engine loads because the cylinder walls are colder and the adiabatic flame temperature during the combustion event is lower which can highly affect the combustion. For this reason, the lowest operable engine load was selected to observe the effect of the intake temperature. The experiments were started when the intake temperature was constant at 160°C, and it was reduced down to 145°C by the 5°C steps. If the intake temperature was above 160°C the combustion event was shifted before the top dead center (TDC) which can give damage to the engine, and if the intake temperature was below 145°C the COV IMEP$_n$ was higher than the required limit of 5%. The start of injection (SOI) was constant at -18°CA, the rail pressure was 400 bar, and the engine speed was 800 rpm during the experiments. Figure 5.1 shows the change at cylinder pressure and heat release rate curves at 2 bar IMEP$_g$ by the intake temperature sweep. It was observed that the maximum in-cylinder pressure was reduced by a lower intake temperature and the combustion event was retarded. The heat release rate (HRR) curves show that a lower intake temperature decreased the combustion speed and HRR curves were wider. In addition to this, it can be said that more heat was released to the exhaust, instead of piston work (Zincir et al., 2019a).

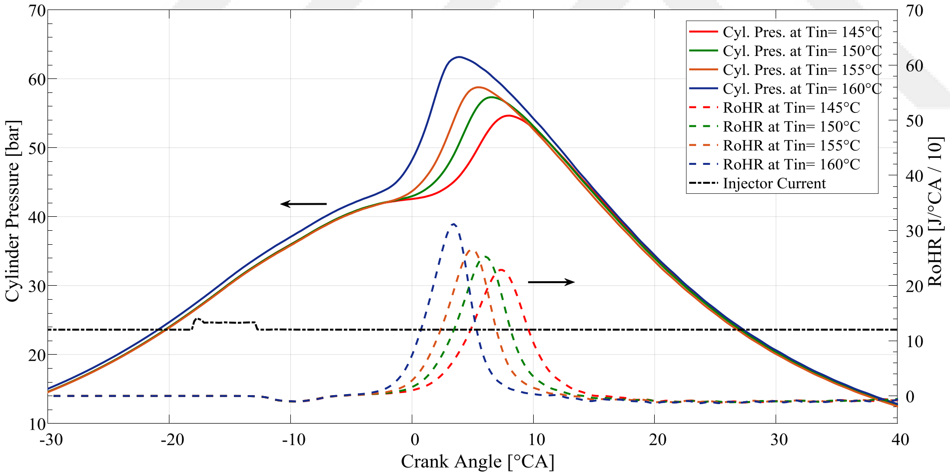

Figure 5.1 : Cylinder pressure and heat release rate curves at 2 bar IMEP$_g$.

The combustion stability was also investigated during the experiments. It was observed that the intake temperature did not affect the COV IMEP$_n$. It was constant at 3% and was not changed with a lower intake temperature. It was not showed the same behavior as the previous study of Zincir et al. (2019a), but the compression ratio was lower with 17.3 at the thesis study which can affect this behavior and need a wider range of intake temperature sweep to observe the effect.

Figure 5.2 shows the change at burn duration and ignition delay at 2 bar IMEP$_g$ by the intake temperature sweep. The burn duration is defined as the time period between CA10 and CA90, which are 10% of the total released heat and 90% of the total released heat, respectively. The ignition delay is defined as the time period between the SOI and CA10. It can be seen that the burn duration was shorter at higher intake temperatures. The combustion event was promoted by the intake temperature and it commences quicker at higher intake temperatures. The burn duration was 17°CA at 145°C but was reduced to 13°CA at 160°C. The ignition delay was also shorter at higher intake temperatures. The reason was a higher intake temperature reduced the resistance of methanol to auto-ignite by a quicker formation of an optimum environment in the cylinder (Zincir et al., 2019a).

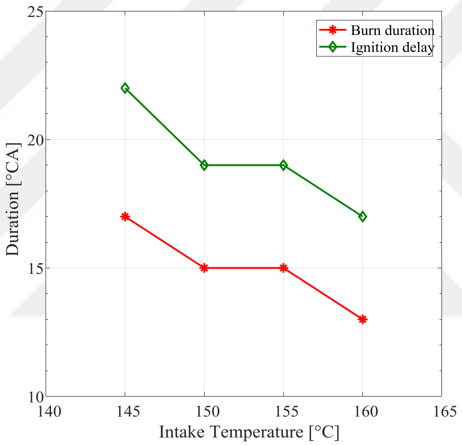

Figure 5.2 : Burn duration and ignition delay at 2 bar IMEP$_g$.

Figure 5.3 shows the change at the combustion phasing and the maximum pressure rise rate by the intake temperature sweep. The combustion phasing (CA50) is the crank angle that the half of the total heat is released. It was observed that at the constant SOI, if the intake temperature is higher, CA50 is closer to TDC. The CA50 was at 6°CA at 145°C while it was at 3°CA AT 160°C. On the contrary, the maximum pressure rise rate (PRR) was higher at higher intake temperatures. The reason is the combustion event is quicker and closer to TDC which increases maximum PRR. It was increased from 6 bar/°CA to 12 bar/°CA from 145°C to 160°C intake temperature.

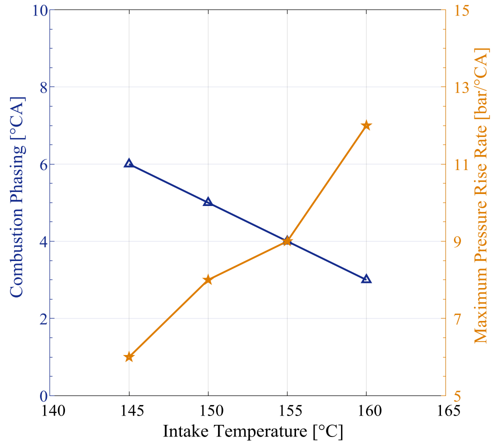

Figure 5.3 : Combustion phasing and maximum pressure rise rate at 2 bar IMEP$_g$.

Figure 5.4 shows the trend of the exhaust temperature and global maximum temperature at 2 bar IMEP$_g$ by the change of the intake temperature. It was observed that the exhaust temperature remained constant between 145°C and 155°C, but it increased slightly from 211°C to 212°C at 160°C intake temperature. It can be said that a higher intake temperature has an effect on the exhaust temperature. The global maximum temperature is the average flame temperature in the cylinder (Zincir et al., 2019a). It can be seen that the global maximum temperature had an increasing trend with a higher intake temperature. It increased from 2004°C to 2207°C from 145°C to 160°C intake temperature, respectively. A higher intake temperature promoted the combustion and increased the maximum in-cylinder pressure which resulted in a higher global maximum temperature.

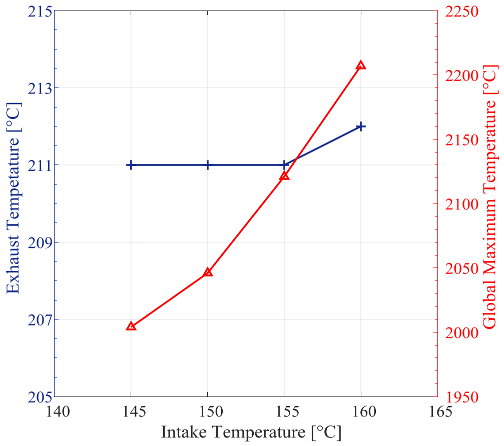

Figure 5.4 : The exhaust temperature and global maximum temperature at 2 bar IMEP$_g$.

The SFC is shown in Figure 5.5. It was 425 g/kWh at 145°C, and then it remained constant at 429 g/kWh at 150°C and 155°C intake temperatures, but it decreased to 418 g/kWh at 160°C intake temperature. The trend of the SFC related to the efficiencies in Figure 5.6. The combustion efficiency was 0.89 and the thermodynamic efficiency was 0.48 at 145°C intake temperature. The combustion efficiency was lower than other operating points, but the thermodynamic efficiency was higher since the combustion event was slower and peak heat release rate was lower which resulted in lower heat loss to the cooling water. However the combustion efficiency was higher with 0.94 at 150°C intake temperature, the SFC was higher with 430 g/kWh at this point. It can be due to a higher heat loss and lower thermodynamic efficiency of 0.45 which required higher fuel consumption to maintain the same engine load. The SFC was the same with 150°C at 155°C intake temperature. The combustion efficiency was higher with 0.96, but the thermodynamic efficiency was lower with 0.44 than the previous point. Both efficiency balanced the situation and the SFC remained constant at this point. The SFC was the lowest one with 418 g/kWh at 160°C. The combustion event was highly promoted with a higher intake temperature which resulted in the highest combustion efficiency of 0.98. In addition to this, the combustion event was advanced with a higher intake temperature that affects the thermodynamic efficiency. It increased to 0.45 at this point. The highest combustion efficiency and moderate thermodynamic efficiency were the reason for the lowest SFC among all operating points.

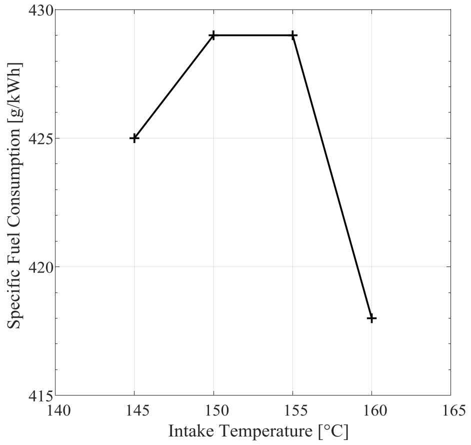

Figure 5.5 : Specific fuel consumption at 2 bar IMEP$_g$.

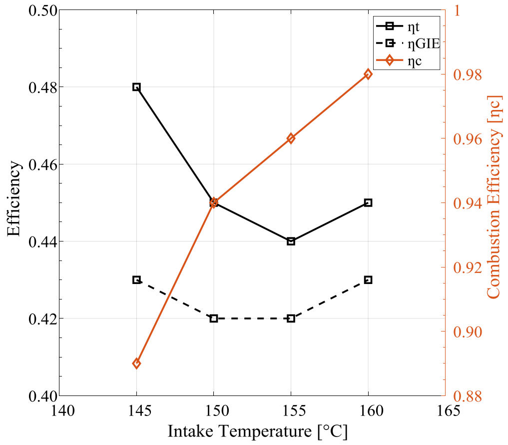

Figure 5.6 : Efficiencies at 2 bar $IMEP_g$.

Figure 5.7 shows the specific emissions by the change of the intake temperature. The CO_2 emission showed a similar trend with the SFC since it depended on fuel consumption. It was 584 g/kWh, 589 g/kWh, 590 g/kWh, and 573 g/kWh at 145°C, 150°C, 155°C, and 160°C intake temperature, respectively. The CO emissions varied from 38 g/kWh to 10 g/kWh from 145°C to 160°C intake temperature. The reason for a higher CO emission at lower intake temperatures can be the effected local fuel/air equivalence ratio, which is the main controller of the CO formation (Heywood, 1988), by the change of the intake temperature. In addition to this, the in-cylinder mixture can be cooled down by the low engine speed and it prevents the oxidation of CO into CO_2 since the in-cylinder temperature is below from the required temperature of 1500 K (Zincir et al., 2019b; Shamun, 2019; Sjöberg and Dec, 2003). The THC emission was 2 g/kWh at 145°C and then it decreased to 0.8 g/kWh at 160°C. Possible reasons of a higher THC emission formation at lower intake temperatures are low maximum in-cylinder temperature (Mendez et al, 2009), longer ignition delay duration and cooling effect of methanol which leads to unburned fuel close to the cold cylinder walls at low loads (Pucilowski et al., 2017). The NO_X emissions varied between 0.02 g/kWh and 0.08 g/kWh from 145°C to 160°C intake temperature. The NO_X emissions were generally too low, due to the low in-cylinder temperature and the intake temperature slightly affected the NO_X emission formation at the low load condition of the engine. The oxygen content of the intake air is reduced with a higher intake temperature (Wang et al., 2017), which can be a reason to prevent a higher amount of NO_X formation by a higher intake temperature.

The NO_X emissions were under the IMO NO_X Tier III Limits which provides a ship to sail even in the ECA region without using an additional after-treatment method.

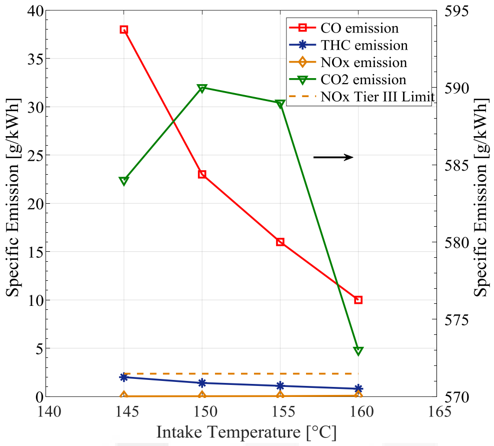

Figure 5.7 : Specific emissions at 2 bar $IMEP_g$.

The engine performance and the emissions of methanol PPC were investigated at 2 bar $IMEP_g$ engine load. The intake temperature sweep was done to observe the sensitivity of the combustion event to the intake temperature change. The findings showed that methanol PPC at 2 bar $IMEP_g$ had good combustion stability and performance. The regulated emissions (CO_2, NO_X, SO_X, PM) were low or zero with methanol PPC at 2 bar $IMEP_g$ engine load. The investigations showed that methanol PPC is suitable to use on ships at low load operation (slow speed navigation) without any combustion stability, engine efficiency or engine emission issues.

5.2 Results Under 3 bar $IMEP_g$ Engine Load

The second experimental load was 3 bar $IMEP_g$ which is around 15% engine load of the engine. It again represents the slow speed navigation of a ship at canal or strait passages.

The engine was operated at 800 rpm constant speed with 1 bar absolute intake pressure, and 400 bar rail pressure. The possible lowest intake temperature was found as 145°C in the previous section. The intake temperature was constant at 145°C. The second important parameter that affects the combustion event after the intake parameters is the injection parameters. For this reason, the SOI sweep was done at 3 bar $IMEP_g$ to observe the effect of the injection timing on the combustion event, engine efficiency, and engine emissions. The SOI was varied from -35°CA to

-28°CA. More advanced SOI timing than -35°CA resulted in a misfire and low combustion stability while more retarded SOI timing than -28°CA resulted in the combustion at the TDC or before the TDC that can damage to the engine. The COV IMEP$_n$ was not affected too much by the SOI sweep. It remained between 2 - 2.5% through all operating points. Wider SOI timing sweep should be done to observe COV IMEP$_n$ variation.

Figure 5.8 shows the cylinder pressure and heat release rate curves by varying the SOI timing. It was observed that the combustion event was advanced with the retarded timing of SOI from -35°CA to -28°CA. The maximum in-cylinder pressure was higher when the SOI was closer to the TDC which has similar behavior with the study of Li (2018). He investigated the effect of the SOI sweep on the combustion event at his experiments. It was observed that when the SOI timing is around -30°CA, the retarded SOI advances the combustion phasing, but when the SOI timing is close to -20°CA the retarded SOI shifts the combustion event to the expansion side. The HRR curves showed that the combustion event was quicker and the peak HRR was higher at the retarded SOI timing. The advanced SOI timing forms leaner and cooled down mixture due to the longer mixing period which results in slower and shifted combustion event.

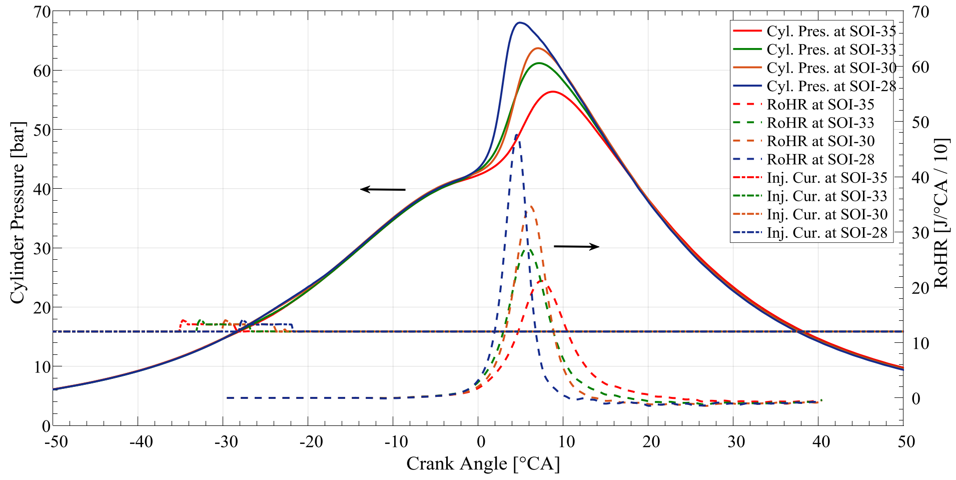

Figure 5.8 : Cylinder pressure and heat release rate curves at 3 bar IMEP$_g$.

The burn duration and the ignition delay variation with the SOI sweep are shown in Figure 5.9. It can be seen that the burn duration decreased from 32°CA to 15°CA with retarding the SOI timing. The combustion event was quicker at retarded SOI timings which can also be seen from the HRR curves. The ignition delay was also reduced from 38°CA to 29°CA with the retarded SOI timing. The combustion event commenced closer to the TDC with the retarded SOI timing that shortens the ignition delay.

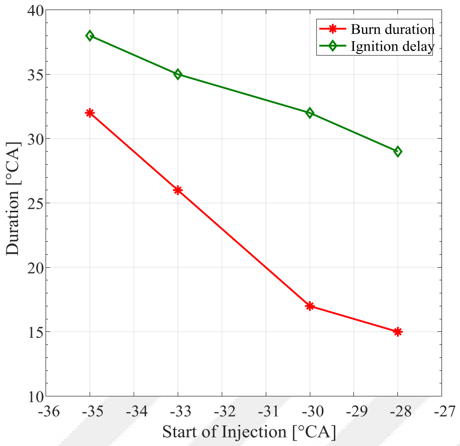

Figure 5.9 : Burn duration and ignition delay at 3 bar IMEP$_g$.

Figure 5.10 shows the combustion phasing and maximum pressure rise rate with the SOI timing sweep. It was observed at the cylinder pressure and HRR curves that the retarding SOI timing resulted in an advanced combustion event. The combustion phasing curve shows that the combustion event happened at 8°CA at SOI-35 and it advanced to 4°CA at SOI-28. The maximum pressure rise rate increased from 6 bar/°CA to 20 bar/°CA by the sweep from SOI-35 to SOI-28. Quicker combustion event close to the TDC with richer fuel regions in the cylinder resulted in sudden pressure rise rates at retarded SOI timings. The PRR above 20 bar/°CA is an advisory limit from Scania for the continuous operation of the engine without any damage to the engine. For this reason, the SOI timing sweep was stopped at SOI-28.

Figure 5.11 shows the exhaust temperature and global maximum temperature with the SOI timing sweep. The exhaust temperature reduced from 248°C to 244°C from SOI-35 to SOI-30, and then it increased to 249°C at SOI-28. The heat loss to the exhaust was lessened until SOI-30 and the optimum operating point for the lowest heat loss to the exhaust was SOI-30. After that SOI timing, the combustion was quicker, PRR was sudden and higher which resulted in higher heat loss to the exhaust. The global maximum temperature curve indicated that in-cylinder temperature was higher with the retarded SOI timing which was in parallel with the maximum PRR curve.

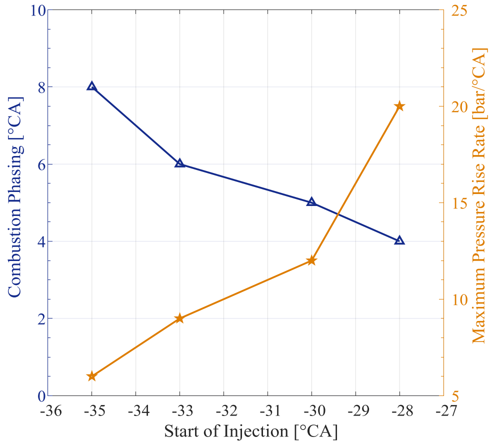

Figure 5.10 : The combustion phasing and maximum pressure rise rate at 3 bar IMEP$_g$.

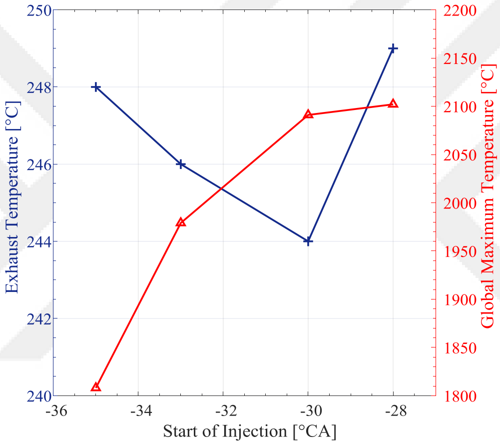

Figure 5.11 : The exhaust temperature and global maximum temperature at 3 bar IMEP$_g$.

The SFC and efficiencies are shown in Figure 5.12 and 5.13, respectively. The SFC curve and thermodynamic efficiency curve were contrary proportional to each other. The SFC reduced from 432 g/kWh to 380 g/kWh from SOI-35 to SOI-30 while the thermodynamic efficiency increased from 0.46 to 0.49 at the same point range. And then the SFC increased to 394 g/kWh and the thermodynamic efficiency reduced to 0.47 at SOI-28. Throughout the operating range, the combustion efficiency increased from 0.92 to 0.99. The combustion of methanol was more complete with the retarded SOI timing due to lesser lean mixture at these operating points that leads to more complete combustion. A higher combustion efficiency provided a closer gap between the thermodynamic efficiency and the gross indicated efficiency.

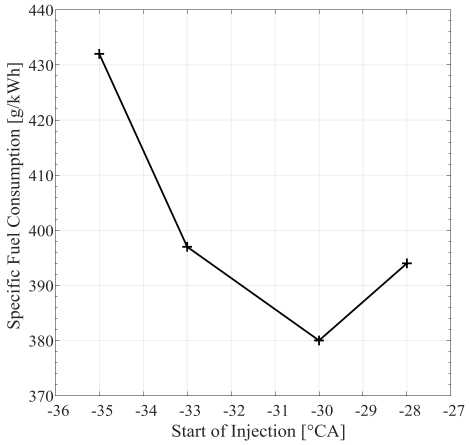

Figure 5.12 : Specific fuel consumption at 3 bar IMEP$_g$.

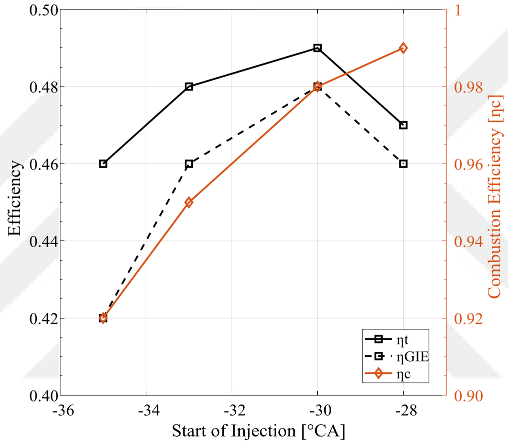

Figure 5.13 : Efficiencies at 3 bar IMEP$_g$.

Figure 5.14 shows the variation of the specific emissions by the SOI timing sweep. The CO_2 emissions showed a similar trend with the SFC since it depended on the carbon content of methanol. The CO_2 emission was 593 g/kWh, 546 g/kWh, 522 g/kWh, and 542 g/kWh at the SOI-35, SOI-33, SOI-30, and SOI-28, respectively. The CO emission was 20 g/kWh at the SOI-35 and it decreased to 5 g/kWh at the SOI-28. The reason for the reduction can be a higher in-cylinder temperature which promoted the CO oxidation to CO_2 emission at the retarded SOI timings. The THC emissions varied between 13 g/kWh and 1 g/kWh from SOI-35 to SOI-28. The combustion was more complete at the retarded SOI timings, the combustion efficiency was the indicator, that resulted in lower THC emissions at the retarded SOI timings. The NO_X emissions were between 0.01 g/kWh and 0.03 g/kWh and they were not affected much from the SOI timing sweep. They were in the range of the IMO NO_X Tier III limits.

The study showed that the specific emissions at 3 bar IMEP$_g$ complied with the rules and regulations in shipping with low NO$_X$ emission and zero SO$_X$ and PM emissions.

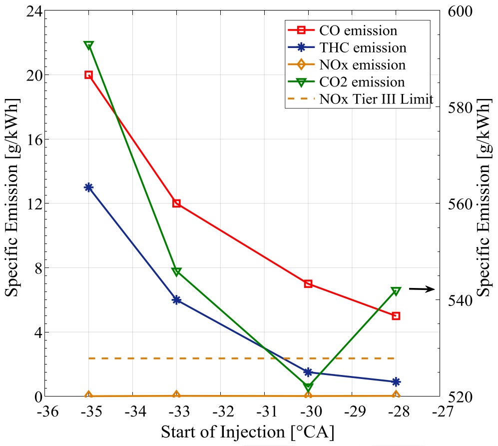

Figure 5.14 : Specific emissions at 3 bar IMEP$_g$.

The study at 3 bar IMEP$_g$ showed that the engine can have good combustion stability, high efficiency and low emissions with the correct SOI timing. The SOI-30 can be the optimum point for high engine efficiency and low engine emissions.

5.3 Results Under 5 bar and 8 bar IMEPg Engine Load

The experiments were continued with 5 bar IMEPg and 8 bar IMEPg engine loads to observe the combustion event, engine efficiency, and engine emissions. These engine loads were around 25% and 40% engine loads, respectively. It represents the slow speed navigation at the canal or strait passage of a ship or slow steaming application at the open sea. The engine speed was 1000 and 1200 rpm and rail pressure was 1000 bar and 1200 bar at 5 bar IMEPg and 8 bar IMEPg, respectively. The intake temperature was constant at 145°C and the intake pressure was 1.2 bar absolute and 1.8 bar absolute 5 bar IMEPg and 8 bar IMEPg, respectively.

Figure 5.15 shows the cylinder pressure and HRR curves at 5 bar IMEPg engine load operation. The single injection was used with the SOI timing at -7°CA at 5 bar IMEPg. The maximum in-cylinder pressure was 82 bar with a burn duration of 10°CA and the ignition delay of 12°CA. The combustion phasing was at 7°CA and the maximum PRR was 21 bar/°CA which was above the adviced limit. The exhaust temperature was 363°C and the global maximum temperature was 1857°C. The SFC was 411 g/kWh. The combustion efficiency was more than 0.99 which was almost complete combustion. The thermodynamic efficiency was 0.44 and the gross indicated efficiency was also almost 0.44 due to the high combustion efficiency. The CO_2 emission was 566 g/kWh, the CO emission was 0.2 g/kWh, the THC emission was 0.2 g/kWh, and the NO_X emission was 1.5 g/kWh which was still under the IMO NO_X Tier III Limit.

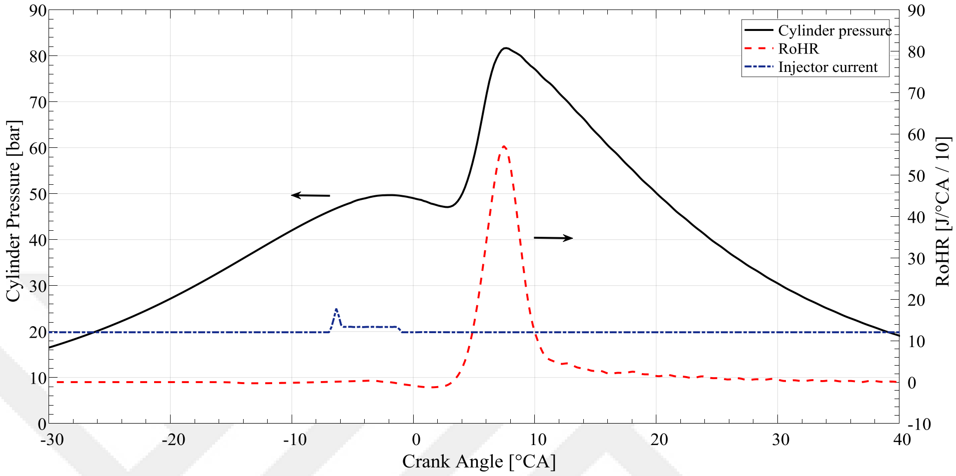

Figure 5.15 : Cylinder pressure and heat release rate curves at 5 bar $IMEP_g$.

Figure 5.16 shows the cylinder pressure and HRR curves at 8 bar IMEPg engine load. The split injection was used at this engine load to reduce the maximum PRR. The first injection was at -20°CA and the second (main) injection was at -5°CA. The maximum in-cylinder pressure was close to 115 bar with a burn duration of 32°CA and the ignition delay of 10°CA. The combustion phasing was at 7°CA and the maximum PRR was 15 bar/°CA. The exhaust temperature was 422°C and the global maximum temperature was 1485°C. The SFC was 390 g/kWh. The combustion efficiency was more than 0.99 which was almost complete combustion. The thermodynamic efficiency was 0.46 and the gross indicated efficiency was also almost 0.46 due to the high combustion efficiency. The CO_2 emission was 537 g/kWh, the CO emission was 0.3 g/kWh, the THC emission was 0.3 g/kWh, and the NO_X emission was 5 g/kWh which was above the IMO NO_X Tier III Limit at the first time until now. But the NO_X emission was at the low Tier II Limit.

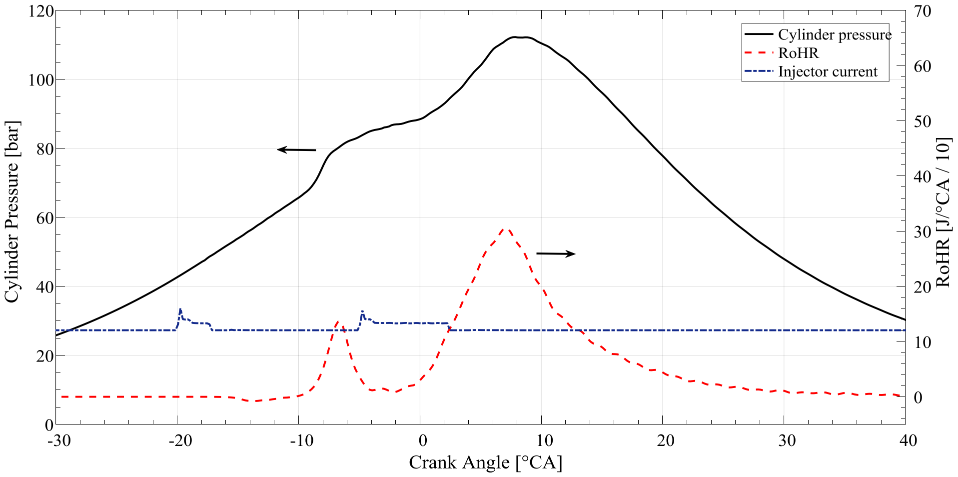

Figure 5.16 : Cylinder pressure and heat release rate curves at 8 bar IMEP$_g$.

5.4 Results Under 10 bar IMEP$_g$ Engine Load

The last engine load at the experiments was 10 bar IMEPg. It was approximately 50% load of the engine. According to Eilertsen (2012), if 25 knots is the 100% propulsion power of a ship, 5 knots of a reduction can result in a 41% propulsion power need. In another study, 100% engine load equals 16 knots of ship speed in the curve and 50% engine load approximately equals 12.5 knots which is 78% of the maximum ship speed (Chang and Chang, 2013). So this engine load represents the 75-80% navigation speed of a ship at open seas. Various investigations were made at 10 bar IMEPg. The differences between the single injection and the split injection of methanol were observed. The first injection sweep, the second injection sweep, the first injection duration sweep, and rail pressure sweep were done during the split injection application. They showed in the figures with the initials of SI for the single injection, FIS for the first injection sweep, SIS for the second injection sweep, FID for the first injection duration, and Prail for the rail pressure sweep. The engine was operated at 1200 rpm constant engine speed, 145°C constant intake temperature, and 2.05 bar absolute intake pressure. The COV IMEPn was constant at 2% that the engine showed good combustion stability at all operating conditions under 10 bar IMEPg.

Figure 5.17 shows the cylinder pressure and HRR curves during the single injection application. The SOI timing sweep was done from -7°CA to -2°CA. It was observed that the combustion event was shifted towards the expansion stroke by more retarded

SOI timing which was in parallel with the study of Li (2018). The maximum in-cylinder pressure reduced with the retarded SOI timing. The HRR curve shapes were different from the previous curves at the lower loads. The combustion type was changed from premixed combustion to the diffusive combustion, due to the longer injection duration. It was essential to keep the SOI timing closer to the TDC at higher loads when it was compared with the low loads. Low in-cylinder temperature and cold cylinder walls at the low load operation of the engine allow using advanced SOI timing. The in-cylinder temperature and cylinder wall temperature are higher at higher engine loads. As a consequence, the SOI timing has to be closer to the TDC to prevent high PRR which can be dangerous for the engine.

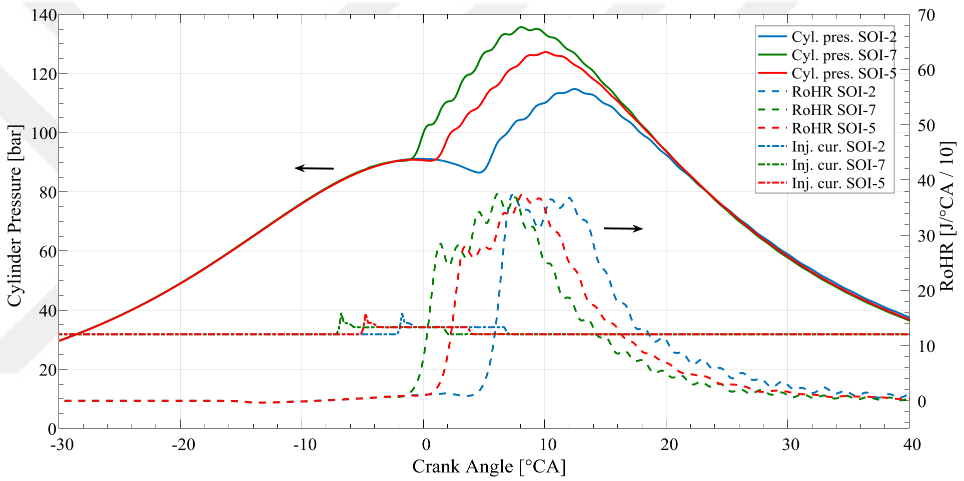

Figure 5.17 : Cylinder pressure and heat release rate curves at 10 bar IMEP$_g$ single injection application.

The split injection strategy was used to observe the effect on the combustion event, engine efficiency, and emissions. The injection parameters affect the combustion event and the combustion is more sensitive to these parameters while the split injection.

Figure 5.18 shows the variation of the cylinder pressure and HRR curves with the first injection timing sweep. The second injection timing was constant at -5°CA and the first injection timing was changed as -23°CA, -20°CA, and -17°CA. It was observed that the first injection did not have any control over the combustion event. The combustion event was commenced at the same crank angle degree at all operating points. The sweep did not change the maximum in-cylinder pressure. The only difference was the shape and timing of the bump before the main combustion event. The shape of this bump affected the maximum PRR. It was higher when the first injection was retarded and closer to the second injection. The HRR showed that the main combustion event was similar at all operating conditions. The only difference was the timing of the preliminary combustion event before the main combustion event. It was also noticed that the combustion type was premixed combustion instead of diffusive combustion like the single injection condition.

The influence of the second injection timing sweep on the cylinder pressure and HRR curves was shown in Figure 5.19. The first injection timing was constant at -20°CA and the second injection timing was changed as -8°CA, -5°CA, and -2°CA. It can be seen from the figure that the second injection was the main controller of the combustion event. When the second injection timing was retarded, the combustion event was shifted towards the expansion stroke. The maximum in-cylinder pressure decreased with the retarded second injection timing since the combustion event was more late and more heat loss to the exhaust was happened. The HRR curves showed briefly that the main combustion event was shifted. The maximum HRR was the same at all operating conditions, but the maximum in-cylinder pressure was lower at retarded second injection timing which was the indicator of the heat loss. The preliminary combustion bumps were almost similar at all operating conditions, except for the second injection timing at -2°CA. It did not happen because of the fuel injection, but due to the slightly higher intake pressure which can be seen at the cylinder pressure curves.

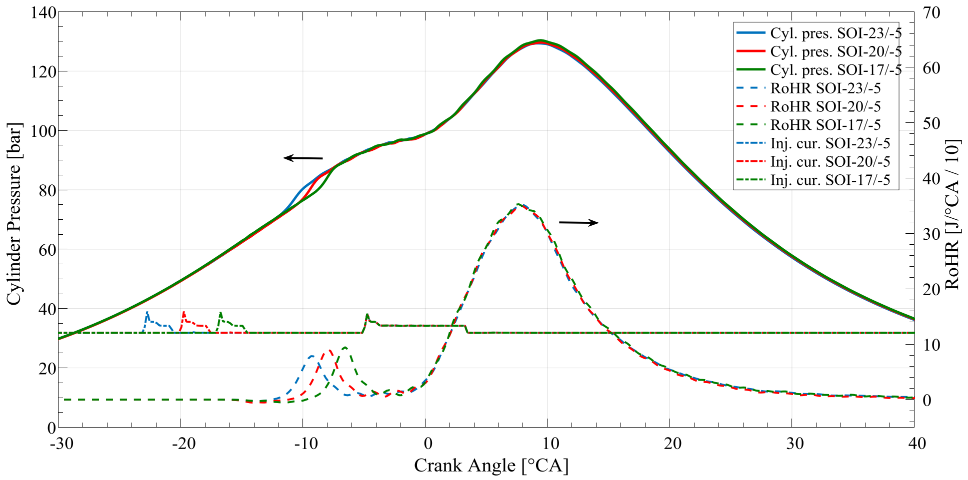

Figure 5.18 : Cylinder pressure and heat release rate curves at 10 bar IMEP$_g$ first injection timing sweep.

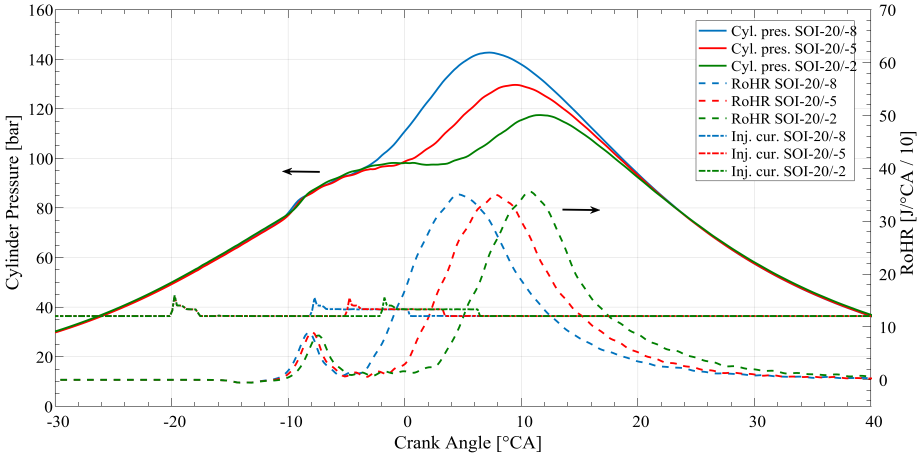

Figure 5.19 : Cylinder pressure and heat release rate curves at 10 bar IMEP$_g$ second injection timing sweep.

Figure 5.20 shows the effect of the first injection duration sweep on the cylinder pressure and HRR curves. The SOI timings of the first injection and the second injection were constant at -20°CA and -5°CA, respectively. The first injection duration was arranged to be 22%, 16%, and 10% of the total injection duration of the first injection and the second injection. It was observed from the cylinder pressure curves that the sweep did not affect the combustion event much. The first bump before the combustion event slightly reduced and the maximum in-cylinder temperature slightly increased with the reduction of the FID. The HRR curves also showed the same behavior with the cylinder pressure curves. The combustion event was remained constant at all operating points. The preliminary combustion bump decreased and the maximum HRR increased with the reduction of the FID.

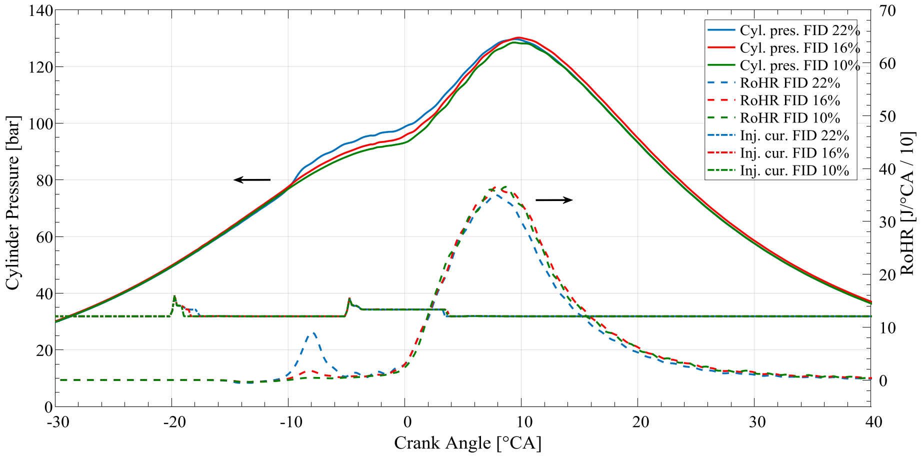

Figure 5.20 : Cylinder pressure and heat release rate curves at 10 bar IMEP$_g$ first injection duration sweep.

The last investigation was the effect of the rail pressure sweep on the combustion event, engine efficiency and engine emissions. The rail pressures of 1000 bar, 1200 bar, and 1400 bar were used at the experiments. Figure 5.21 shows the cylinder pressure and HRR curves by the variation of the rail pressure. To maintain the combustion event at the same crank angle degree at all operating points, the injection duration and the second injection timings were varied. The first injection timings remained constant. It can be seen that the maximum in-cylinder pressure was almost the same at the rail pressures of 1200 bar and 1400 bar, but it was slightly lower at 1000 bar rail pressure. The HRR curves showed that the maximum HRR value was lower and the preliminary bump had a higher value at 1000 bar rail pressure. The rail pressure had a small influence on the first bump and the main combustion curve, but the change on the first injection duration could also affect the curve.

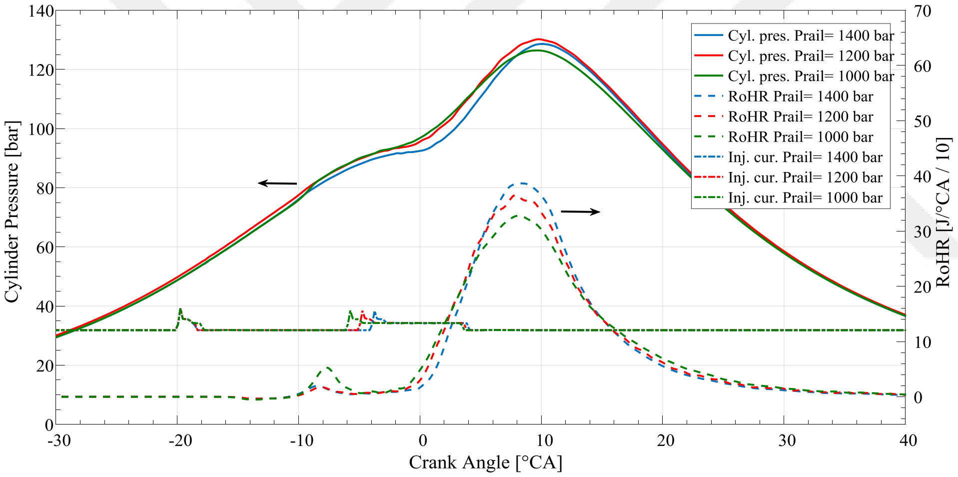

Figure 5.21 : Cylinder pressure and heat release rate curves at 10 bar $IMEP_g$ rail pressure sweep.

The combustion properties, engine efficiency, and emissions of the operating points at 10 bar $IMEP_g$ were compared between Figure 5.22 and 5.31. FID is the first injection duration, FIS is the first injection timing sweep, Prail is the rail pressure sweep, SI is the single injection, and SIS is the second injection timing sweep in the figures. Orange color represents the most advanced injection timing, the highest injection duration percentage, or the lowest rail pressure. The dark blue color is the operating point in the middle of the sweeps, and yellow color is the most retarded injection timing, the least injection duration percentage, or the highest rail pressure.

Figure 5.22 shows the burn duration of the operating points at 10 bar IMEP$_g$. It was observed that the burn duration was constant at 30°CA during the FID sweep. The burn duration decreased from 34°CA to 30°CA by the FIS from -23°CA to -17°CA. The preliminary combustion was shifted towards the main combustion event which resulted in a shorter burn duration period. The rail pressure sweep from 1000 bar to 1400 bar decreased the burn duration from 34°CA to 29°CA. A higher rail pressure could increase the mixing of the air-fuel which provided a more optimum condition for a quicker combustion event. The SOI timing sweep from -7°CA to -2°CA at the single injection slightly affected the burn duration. The burn duration increased from 16°CA to 17°CA, but in general trend, the combustion event was shifted as the same crank angle degree as the SOI timing sweep. The SIS increased the duration of the combustion from 30°CA to 35°CA by the second injection timing sweep from -8°CA to -2°CA. Since the crank angle between the first injection timing and the second injection timing was longer with the retarded second injection timing, the combustion event was longer.

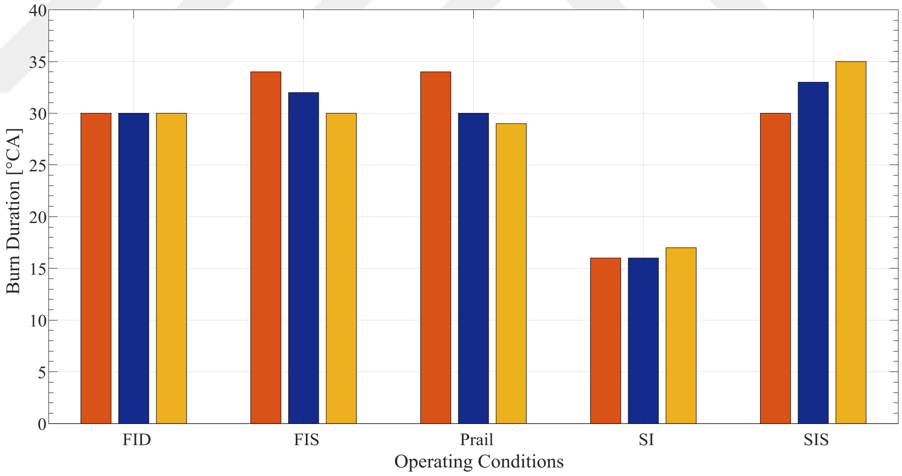

Figure 5.22 : Burn duration comparison at 10 bar IMEP$_g$.

Figure 5.23 shows the ignition delays of the operating points at 10 bar IMEP$_g$. It can be seen that the FID sweep, the rail pressure sweep, and the SIS did not affect the ignition delay and it was constant at 10°CA. In addition to these, the ignition delay was constant at 8°CA during the operation with the single injection, because the combustion event was shifted with the SOI timing sweep. The FIS decreased the ignition delay from 11°CA to 7°CA from the first injection timing of -23°CA to -17°CA.

The preliminary combustion event was slightly shifted with the first injection timing, but it was not shifted as the same crank angle as the first injection timing and the ignition delay was shortened.

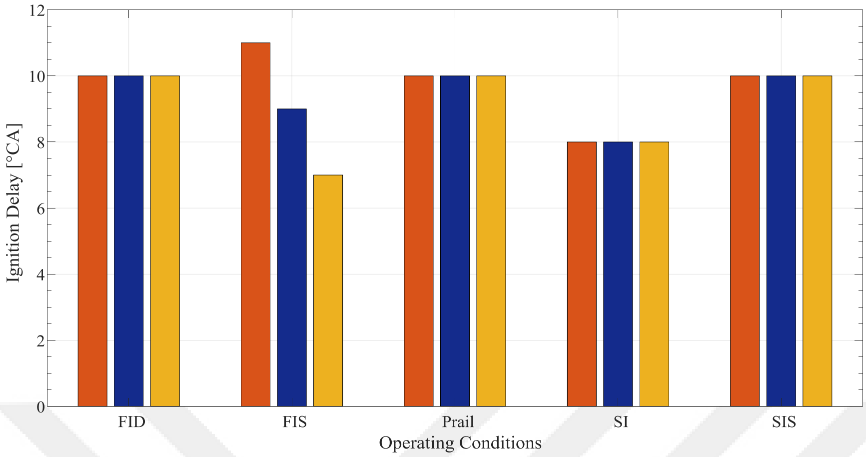

Figure 5.23 : Ignition delay comparison at 10 bar $\mathrm{IMEP_g}$.

Figure 5.24 shows the combustion phasings of the operating points at 10 bar $\mathrm{IMEP_g}$. The FIS and the rail pressure sweep did not affect the combustion phasing and it remained constant at 8°CA and 9°CA for the FIS and the rail pressure sweep, respectively. The FID sweep slightly affected the combustion phasing that was retarded 1°CA by the FID from 22% to 10%. The SI sweep and the SIS sweep affected the combustion phasing because the combustion event depended on these injection timings. The second injection timing is the main controller of the combustion event (Panakarajupally and Mittal, 2017). The combustion phasing was retarded with the retarded injection timings.

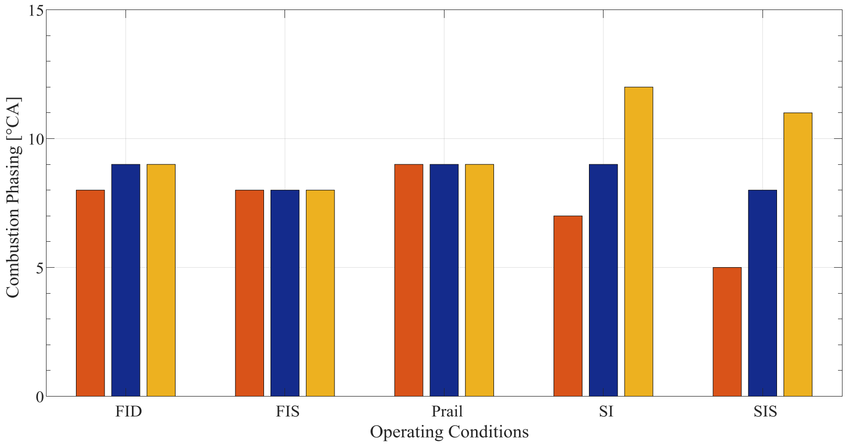

Figure 5.24 : Combustion phasing comparison at 10 bar $\mathrm{IMEP_g}$.

The maximum PRRs of the operating points at 10 bar IMEP$_g$ were shown in Figure 5.25. The FID sweep decreased the maximum PRR from 13 bar/°CA to 12 bar/°CA by a lower percentage of the first injection duration. It was because the first injection is the controller for the PRR. The FIS increased the maximum PRR from 11 bar/°CA to 13 bar/°CA since it was observed that the maximum PRR was higher when the first injection and the second injection timings were closer to each other. After the preliminary combustion event by the first injection, if the second injection timing is closer the main combustion event commences quickly after the preliminary combustion event which results in a higher maximum PRR. The rail pressure sweep increased maximum PRR from 9 bar/°CA to 12 bar/°CA. The methanol fuel was more pulverized at higher rail pressures which form a more premixed mixture (Sun et al., 2016), promotes the combustion event, and resulted in a higher maximum PRR. The SIS slightly affected the maximum PRR. The maximum PRR decreased with the retarded second injection timing that shifted the combustion event to the expansion stroke and reduced the maximum PRR. It can be seen that the single injection condition had an extremely higher maximum PRR, which can give damage to the engine in a long period, than the split injection conditions. The second injection or even a third injection reduces the fast combustion event in the medium-to-high engine loads (Benajes et al., 2017). It can also be seen that the maximum PRR decreased with the retarded injection timing.

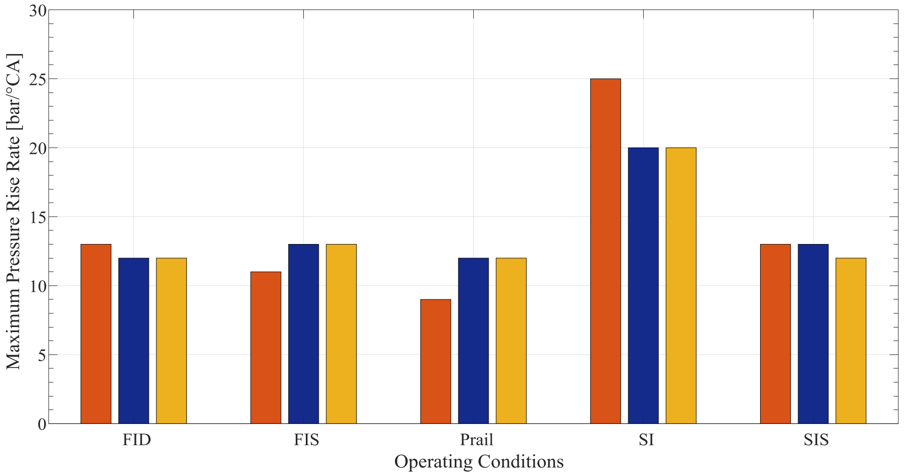

Figure 5.25 : Maximum pressure rise rate comparison at 10 bar IMEP$_g$.

Figure 5.26 shows the specific fuel consumption of the operating points at 10 bar IMEP$_g$. It can be seen in the figure that there are not many differences between the operating points of the split injection cases. The SFC increased with the FID sweep from 22% to 10% and the SIS from -8°CA to -2°CA. On the other hand, the single injection case had slightly higher SFC than the split injection cases. The maximum SFC value was 391 g/kWh for the split injection cases while it was 393 g/kWh for the single injection case.

Figure 5.27 shows the thermodynamic efficiency of the operating points at 10 bar IMEP$_g$. The efficiency varied between 0.46 and 0.47, and there were slight differences between the operating points. The combustion efficiency was above 0.99 at all operating points and the gross indicated efficiency was almost the same as the thermodynamic efficiency. For these reasons, they were not shown in the figures. The SI sweep did not affect the thermodynamic efficiency and it remained at 0.46. It was observed that when the first injection and the second injection were closer to each other at the FIS and the SIS the thermodynamic efficiency was higher. There was no significant efficiency trend at the rail pressure sweep. The reduction in the percentage of the FID decreased the thermodynamic efficiency since the main combustion heat release increased and more heat loss could be observed.

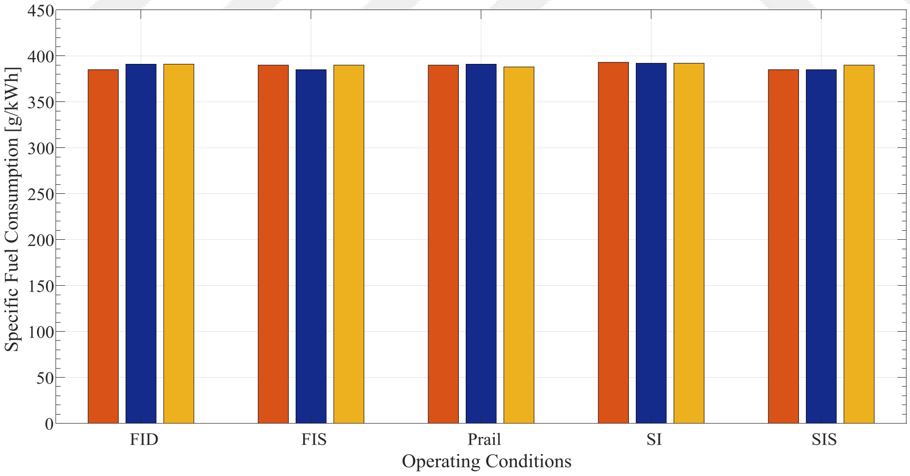

Figure 5.26 : Specific fuel consumption comparison at 10 bar IMEP$_g$.

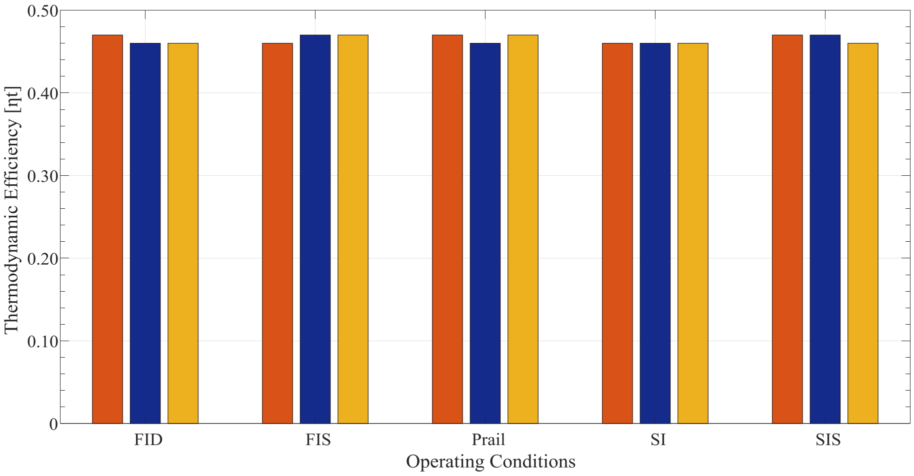

Figure 5.27 : Thermodynamic efficiency comparison at 10 bar IMEP$_g$.

The CO_2 emissions of the operating points at 10 bar IMEP$_g$ are shown in Figure 5.28. There were no significant variations at the FIS, the rail pressure sweep, and the SI sweep. The only noticed thing was the SI had a slightly higher CO_2 emission than the split injection cases related to the SFC. The CO_2 emissions raised to 538 g/kWh from 529 g/kWh from the FID of 22% to 10% which again related to the SFC. The SIS from -8°CA to -2°CA increased the CO_2 emissions from 529 g/kWh to 537 g/kWh, due to a higher SFC.

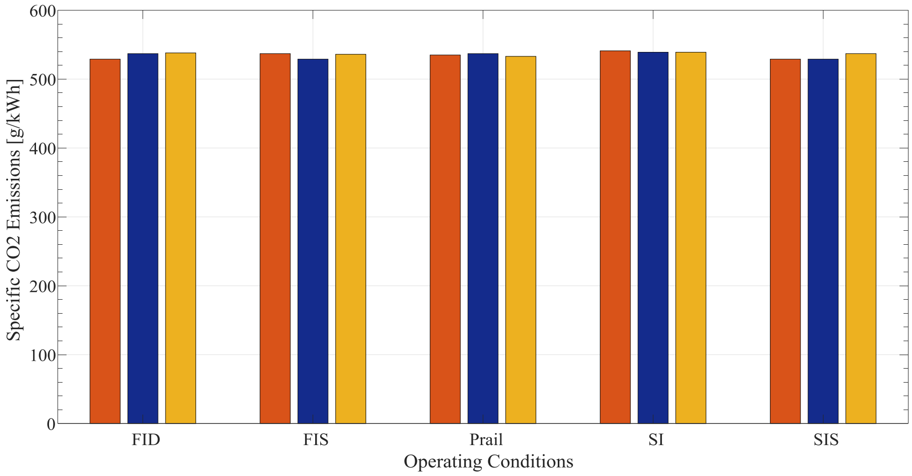

Figure 5.28 : CO_2 emission comparison at 10 bar IMEP$_g$.

The CO emissions of the operating points at 10 bar IMEP$_g$ are shown in Figure 5.29. They varied between 0.2 g/kWh and 0.3 g/kWh. In general, the in-cylinder temperature was optimum for the oxidation of the CO to the CO_2 emission which resulted in low CO emissions at all operating points. There were not significant emission trends, except for the rail pressure sweep and the SIS. A higher rail pressure changed the local fuel/air ratio which affects the CO emission formation. The fuel jet penetrated highly into the charge and the in-cylinder charge could be leaner with a higher rail pressure that increased the oxidation of the CO and reduced the CO emissions. The CO emissions increased with the retarded second injection timing. A change at the injection timing could affect the local fuel/air ratio resulted in higher CO emissions.

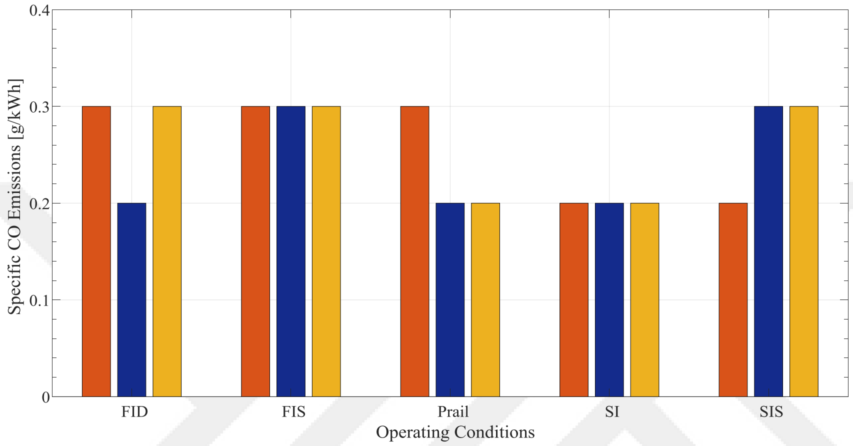

Figure 5.29 : CO emission comparison at 10 bar IMEP$_g$.

Figure 5.30 shows the THC emissions of the operating points at 10 bar IMEP$_g$. It can be seen that the THC emission was 0.2 g/kWh at all operating points. The combustion event was close to complete and the combustion efficiency was above 0.99 at all operating points.

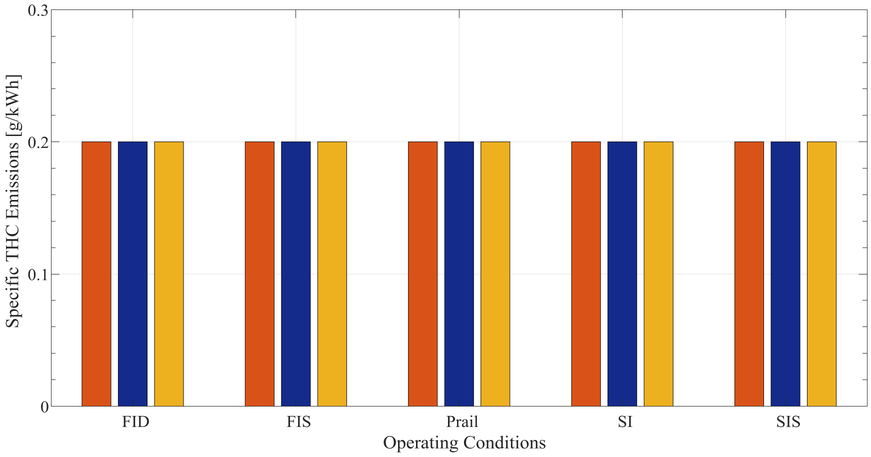

Figure 5.30 : THC emission comparison at 10 bar IMEP$_g$.

Figure 5.31 shows the NO_X emissions of the operating points at 10 bar $IMEP_g$. All of the operating points are in the range of the NO_X Tier II Limit. The NO_X emissions were 6 g/kWh, 4.5 g/kWh, and 5 g/kWh at the FID sweep of 22%, 16%, and 10%. The NO_X emission was 6 g/kWh at 22% since there was a higher maximum PRR. This affected the maximum in-cylinder temperature and the NO_X formation. The NO_X emissions were 5.5 g/kWh, 6 g/kWh, and 5 g/kWh at -23°CA, -20°CA, and -17°CA, respectively. The emissions were close to each other. The local fuel/air ratio plays a role in the formation of NO emissions (Heywood, 1988), and it could be the reason for the variation. The effect of the rail pressure sweep was insignificant because the NO_X emissions were between 4 g/kWh and 4.5 g/kWh. The NO_X emissions were 5.5 g/kWh, 6 g/kWh, and 4 g/kWh at -8°CA, -5°CA, and -2°CA, respectively. The local mixture proportion in the cylinder and lower maximum PRR at the retarded second injection timing resulted in a lower NO_X emission. The SI sweep had higher NO_X emissions than the split injection cases at the SOI of -7°CA and -5°CA with 8.5 g/kWh and 7 g/kWh, respectively. The reason could be high maximum PRR, high in-cylinder temperature. When the local fuel/air ratio was changed with the injection timing sweep, the NO_X emissions decreased.

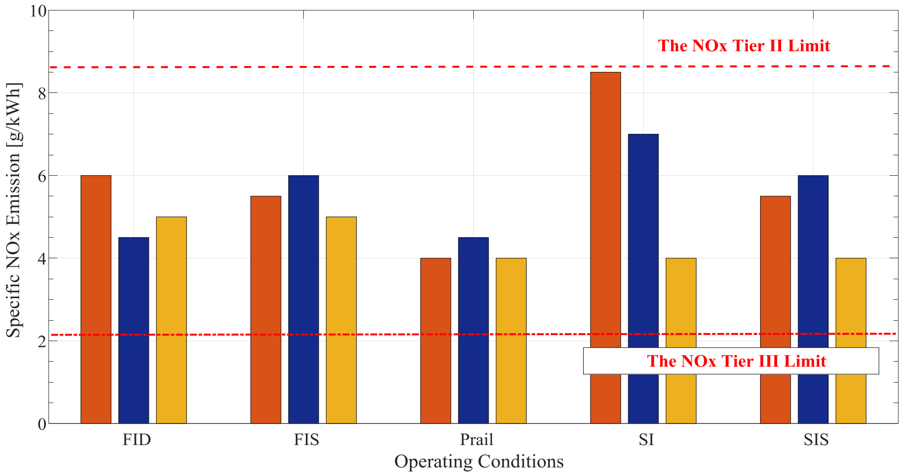

Figure 5.31 : NO_X emission comparison at 10 bar $IMEP_g$.

The experimental studies at 10 bar $IMEP_g$ showed that the combustion stability was good with the COV $IMEP_n$ of 2%. The gross indicated efficiency was between 0.46 and 0.47, and the combustion efficiency was above 0.99. The CO emissions and the THC emissions were low and the NO_X emissions were in the range of Tier II Limit. These studies were done by using zero EGR. The success of the EGR to mitigate

NO_X emissions is well-known. It decreases the speed of the combustion event and cools down the combustion chamber that reduces the NO_X formation. The previous studies (Shamun et al., 2016; Shamun et al.; 2017b) on the same heavy-duty engine with the engine in the thesis study showed that by using up to 50% EGR while applying methanol PPC, the NO_X emission was below Euro VI limit of 0.4 g/kWh (Williams and Minjares, 2016). It means the NO_X emissions under Tier III limits can be achieved by using EGR.

5.5 Predictions for Higher Engine Loads

The engine was able to be operated up to 10 bar $IMEP_g$ engine load which corresponds to 50% engine load. The engine had an overheating problem that could not be solved during the experimental studies. It limited the experimental study load range at 10 bar $IMEP_g$.

To predict the trend of the SFC, engine efficiencies, and emissions at higher loads than 10 bar $IMEP_g$, the curve fitting was applied to the gathered experimental data until 10 bar $IMEP_g$ and approximate trends were plotted.

Figure 5.32 shows the SFC prediction at all load range. The operating parameters of the engine including engine speed, intake pressure, common rail pressure, and fuel injection timing were not the same during the experiments and they were changed to maintain the optimum operation of the engine for each engine load. For this reason, there is a fluctuation in the SFC experimental data plot.

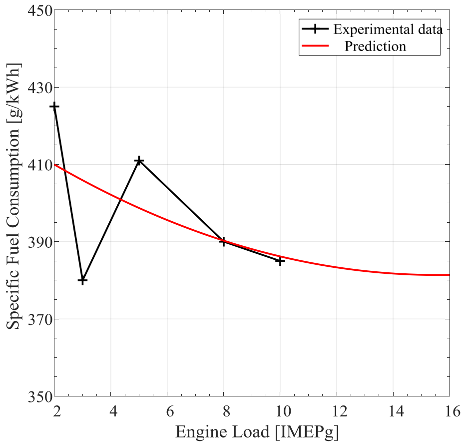

Figure 5.32 : The specific fuel consumption prediction.

Despite the fluctuation, the SFC prediction curve was plotted to show the approximate trend of the SFC at higher engine loads. The SFC prediction curve decreases until 381 g/kWh at 16 bar IMEP$_g$ engine load.

Figure 5.33 shows the combustion efficiency at all load range. The combustion efficiency was 0.89 at 2 bar IMEP$_g$, but it increased above 0.99 at 10 bar IMEP$_g$. According to the prediction curve, it will continue at the constant value until 16 bar IMEP$_g$. Figure 5.34 shows the thermodynamic efficiency and Figure 5.35 shows the gross indicated efficiency at all load range.

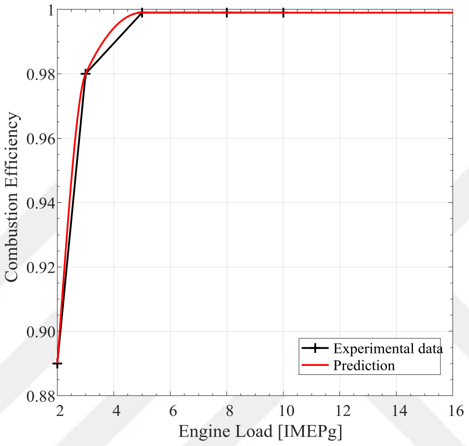

Figure 5.33 : The combustion efficiency prediction.

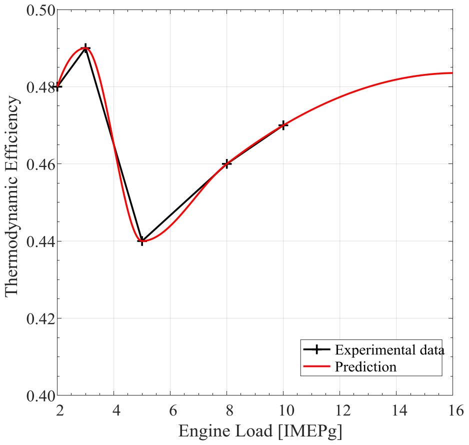

Figure 5.34 : The thermodynamic efficiency prediction.

Both efficiencies had ups and downs during the experiments according to the operating conditions. When the curve fit was done using these values, the prediction curve shows the highest efficiency at 0.485 at 16 bar IMEP$_g$.

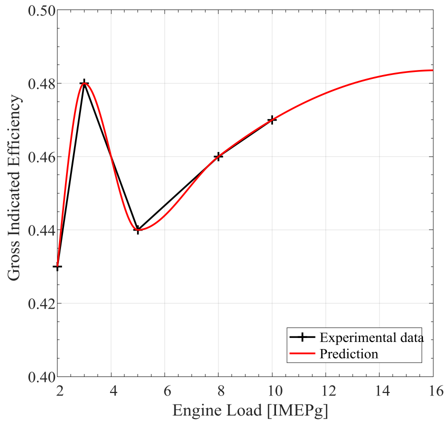

Figure 5.35 : The gross indicated efficiency prediction.

A prediction for the CO_2 emission is shown in Figure 5.36. The CO_2 emission depends on the SFC, but the prediction curve of the CO_2 emission by using experimental data is different from the SFC prediction curve. The CO_2 emission prediction always decreases until the full engine load. For this reason, the SFC values of 12 bar, 14 bar, 16 bar $IMEP_g$ were gathered from the prediction curve in Figure 5.32 and added to Figure 5.36. The CO_2 emission prediction curve was plotted by using both the experimental data until 10 bar $IMEP_g$ and the SFC prediction curve data from Figure 5.32. Again, there is a fluctuation in the plot between 2 bar to 8 bar $IMEP_g$ which is due to the different operating parameters at these loads explained for the SFC prediction curve. The lowest CO_2 emission was 524 g/kWh at 16 bar $IMEP_g$.

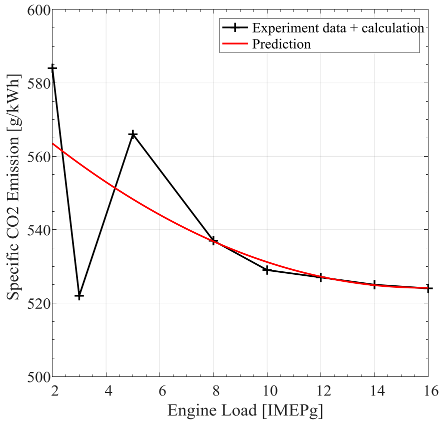

Figure 5.36 : The specific CO_2 emission prediction.

Figure 5.37 shows the CO emission at all engine loads. It was 38 g/kWh, 7 g/kWh, 0.2 g/kWh, 0.2 g/kWh, and 0.2 g/kWh at 2 bar, 3 bar, 5 bar, 8 bar, and 10 bar $IMEP_g$ engine load.

The curve fit was done by using these experimental data points. The prediction curve shows that it will continue as the constant at 0.2 g/kWh under higher loads than 10 bar IMEP$_g$.

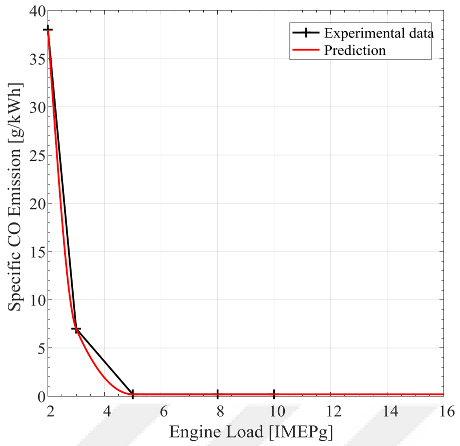

Figure 5.37 : The specific CO emission prediction.

A prediction for the THC emission at all load range is shown in Figure 5.38. The THC emissions were 2 g/kWh at 2 bar IMEP$_g$ and it decreased to 0.2 g/kWh at 10 bar IMEP$_g$, due to more complete combustion event. The curve fit was done and the prediction curve shows that the THC emission will remain constant at 0.2 g/kWh until 16 bar IMEP$_g$.

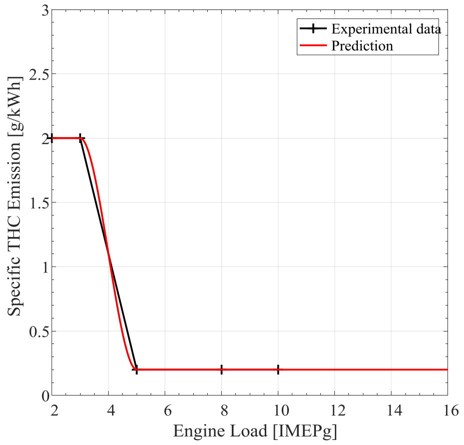

Figure 5.38 : The specific THC emission prediction.

Figure 5.39 shows the NO$_X$ emission at all load range. The NO$_X$ emissions were started with 0.02 g/kWh at 2 bar IMEP$_g$ and increased up to 5.5 g/kWh at 10 bar IMEP$_g$. The only suitable curve for the fitting to these experimental data was the linear fitting.

For this reason, the NO_X emissions always increase during the all load range. The NO_X emission is in the range of the NO_X Tier III Limit until 5.5 bar $IMEP_g$, and in the range of the NO_X Tier II Limit until 13.5 bar $IMEP_g$.

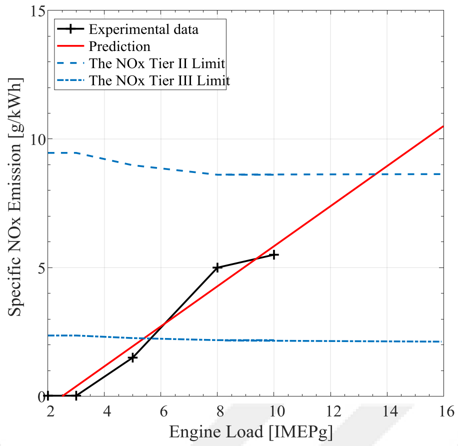

Figure 5.39 : The specific NO_X emission prediction.

According to the prediction, the NO_X emission will be above the NO_X Tier II Limit after that engine load. This prediction is done by using experimental data without EGR. The previous studies showed that the NO_X emission level can be decreased below 0.4 g/kWh by using high EGR levels under the methanol PPC concept.

6. CONCLUSION

This section includes comments about the findings, contributions of the thesis study, and limitations of the research sections to conclude the study.

6.1 Discussion about the Thesis Study

The energy demand and air pollution are the two important things recently for the industry, transportation, and buildings. Maritime transportation has major importance in the transportation sector since a large portion of international trade is done by using maritime transportation. The ships consume a huge amount of fuel and emit a remarkable amount of emissions into the atmosphere. The shipping emissions have a contribution to global warming, climate change, and declining air quality. Especially, near-coastal navigation negatively affects human health and cultivated areas. The most important emission types are CO_2, NO_X, SO_X, and PM which are regulated by the IMO to control and mitigate these emissions. The rules and regulations will be stricter day-by-day and it is hard for the ship owners or management companies to cope with the legislation. There are various technologies including exhaust gas recirculation, selective catalytic reactors, SO_x scrubbers, etc. to reduce shipping emissions. Using alternative fuels other than conventional fossil fuels is another emission abatement method, and it is popular nowadays. The alternative fuels such as LNG, LPG, and methanol have been started to use on the ships. The advantage of alternative fuels over the emission abatement technologies is these alternative fuels can reduce various emission types at once on the other side the emission abatement technologies can reduce only one specific emission type and can increase other types of emissions. Besides its advantages, it is important to select appropriate alternative fuel for ships since there are various points on a ship to consider before the selection of alternative fuel.

The thesis study comprises two main sections. The first section was the formation of an assessment model for alternative fuels by considering different aspects in the maritime industry and evaluate them by the various criteria to find the suitability of the alternative fuels for using on ships. The second section was the experimental study part of the thesis. The combustion properties, engine performance, and engine emissions were investigated and discussions were made. The main outcome of the thesis study was the evaluation of the alternative fuels, finding the suitable ones for ships, and doing an experimental study with one of the suitable alternative fuels found by the assessment model. The thesis study showed that the alternative fuel selected for the thesis study was suitable for commercial ship use, and the combustion of this alternative fuel had promising results.

6.1.1 Comments about the first part of the thesis study

In the first part of the thesis before the formation of the assessment model, the alternative fuels used in the study were determined. The literature search was done from Google Scholar to find academic interest in alternative fuels. 36 alternative fuels were found with the total research number of 537961. The significant research number was determined as 15000 to reduce the number of alternative fuels for the thesis study. 14 alternative fuels were above the limit of 15000 research numbers. However there were 14 alternative fuels above the range of 15000 research numbers, half of these alternative fuels were used for the production of bio-diesel. As a consequence, waste cooking oil, palm oil, corn oil, pyrolysis oil, rapeseed oil, and soybean oil were not included in the study. On the other hand, ammonia, ethanol, hydrogen, kerosene, LNG, LPG, and methanol were the evaluated alternative fuels by the assessment model.

The core of the assessment model was the AHP tool, which is one of the popular multi-criteria decision-making tools. The assessment criteria were determined by taking into consideration of the previous studies. The main criteria were safety, legislation, reliability, technical, economy, and ecology. And there were various sub-criteria of the safety, reliability, and economy main criteria. The criteria weightings were calculated by gathering opinions of 14 experts while the alternative fuel weightings for criteria were calculated by earned pair-wise comparison points at each criterion. The main criteria weightings were 0.346, 0.090, 0.090, 0.025, 0.046, and 0.346 for the safety, legislation, reliability, technical, economy, and ecology, respectively.

The safety and the ecology main criteria were the most important ones according to expert opinions. On the contrary, the technical criterion was the least important one.

After using properties of the alternative fuels and received points during the evaluation at the specific criteria, pair-wise comparison of one alternative fuel to others was done, and then AHP weighting tables were constituted. By using the weightings of the main criteria the total performance weightings of the alternative fuels were calculated. LNG had the highest weighting of 0.234 which means it is the most suitable alternative fuel for ships. Methanol was the second most suitable alternative fuel with the weighting of 0.151, and ammonia was the third most suitable alternative fuel with the weighting of 0.148. The least suitable alternative fuel for ships was kerosene with the weighting of 0.065, according to the result of the assessment model.

The assessment model findings and the recent alternative fuel developments in the maritime industry were in parallel. LNG is the most popular alternative fuel in the maritime industry with a remarkable number of LNG-fuelled commercial ships and new ship orders. Methanol is a promising alternative fuel for ships, there are some methanol-fuelled commercial ships in operation and various maritime-based projects have been ongoing. The surprise of the assessment model is ammonia since the researchers have lost their attention and there are not too many up to date studies in the literature. Although there have not many recent studies in the literature, MAN has been working on using ammonia at its engines. Also, it has been used in SCR systems as a NO_X abatement technology. Urea in the SCR system reacts in the catalyst and changed into ammonia. The maritime sector is familiar with ammonia, and it can be one of the alternative fuels if the maritime industry studies will focus on ammonia as a ship fuel. The remaining ordering of the alternative fuels was hydrogen, ethanol, LPG, and kerosene. These alternative fuels have lower suitability, but they can still be used on ships. There are hydrogen fuel cell-powered ships in operation, there are some projects with ethanol, and there are some LPG-fuelled ships in operation. Kerosene has the least change to be used on ships as fuel, but it is still an option for the shipping fuel. This study shows that the assessment model matches the sector reality.

6.1.2 Comments about the second part of the thesis study

The second part of the thesis study was the experimental study with an alternative fuel to investigate the combustion properties, engine performance, and engine emissions. LNG, methanol, and ammonia were found to be the top three most suitable alternative fuels for ships by the assessment model in the first part of the thesis study. Methanol was selected as the experiment fuel since it has taken the attention of the researchers in recent years. There have been some commercial applications, but it is not many in number. On the other hand, LNG has a remarkable number of commercial application and it has been proofed by the excessive amount of researches. It is a transition period for methanol from experimental-based applications to the commercial-based applications, and it is a good opportunity to do an experimental study with methanol and include in the literature. Another advantage of methanol is it is in a liquid state at standard temperature and pressure, less toxic than ammonia and less safety precaution than LNG is needed for the experimental studies.

There are various combustion types to burn methanol in diesel engines, but the PPC concept was applied at the experimental study. The reasons to select the PPC concept were lesser modification need on the engine and the related systems, possibility of the high engine efficiency, low NO_X and PM emissions, one of the recent combustion concepts which has possibility to fill the gap in the literature, and possibility of the application of the PPC concept on a marine engine.

The experimental studies were done on a six-cylinder Scania D13 heavy-duty engine modified to run on only one cylinder. The operated engine loads were 2 bar, 3 bar, 5 bar, 8 bar, and 10 bar $IMEP_g$ engine loads. The combustion properties, engine efficiency and engine emissions of the methanol PPC concept were investigated.

The experiments started with 2 bar $IMEP_g$ which is the possible lowest operable engine load since COV $IMEP_n$ was higher than the upper limit of 5%, and the CO and HC emissions were above the limit of the measurement range of the emission analyzer when the engine load was lower than 2 bar $IMEP_g$. This engine load is 10% of the maximum engine load and represents the deadslow sailing of a ship while entering a port, leaving a port, canal or strait passage. The intake temperature sweep was done from 160°C to 145°C by the 5°C steps since the intake temperature is an important parameter for the combustion of methanol at the PPC concept. The sensitivity of the combustion event to the intake temperature sweep was observed. According to the experimental findings, the methanol PPC concept at 2 bar $IMEP_g$ had good combustion stability and high engine efficiency up to 0.48. It was observed that lower intake temperature slowed down the combustion event, increased the ignition delay, reduced the maximum in-cylinder temperature, decreased the maximum PRR and shifted the combustion phasing crank angle. The CO and THC emissions depended on the intake temperature and they increased with lower intake temperatures. On the other hand, the CO_2 emission depended on the SFC. The NO_X emission was slightly higher at higher intake temperatures, but it was extremely low and under the IMO NO_X Tier III Limit at all intake temperature conditions. The findings showed that methanol PPC is suitable to use on ships at slow speed navigation without any combustion stability, engine efficiency or engine emission issues.

The experiments were continued with 3 bar $IMEP_g$ which was 15% of the maximum engine load and represents the slow speed navigation of a ship at canal or strait passages. The sensitivity of the combustion event to the SOI timing was investigated at this engine load. The SOI timings were -35°CA, -33°CA, -30°CA, and -28°CA. It was observed that the combustion event was advanced closer to the TDC with more retarded SOI timing. The maximum in-cylinder pressure was increased, the combustion event was quicker, the ignition delay period was shorter, and the maximum PRR was higher with the retarded SOI timing. The combustion efficiency was higher with the retarded SOI timing, and the thermodynamic efficiency was the optimum at SOI-30°CA with 0.49. The CO_2 emission depended on the SFC and engine efficiency. The CO and THC emissions were lower at the retarded SOI timings. The NO_X emission was extremely low at the all operating range and it was slightly increased with the retarded SOI timing. It was in the range of the IMO NO_X Tier III Limit.

The experiments were commenced at 5 bar and 8 bar $IMEP_g$ which are 25% and 40% of the maximum engine load. It was aimed to observe the combustion event, engine efficiency, and engine emissions at these loads which represent the slow speed navigation at the canal or strait passage of a ship or slow steaming application at open sea. The combustion efficiency was above 0.99 at both engine loads. The thermodynamic efficiency was 0.44 and 0.46 at 5 bar and 8 bar IMEP_g engine loads, respectively. The CO emission and the THC emission were low at both engine loads, due to almost complete combustion event. The NO_X emission was 1.5 g/kWh at 5 bar IMEP_g which is under the IMO Tier III Limit, but it increased to 5 g/kWh at 8 bar IMEP_g that is above the IMO Tier III Limit and needs additional after-treatment measures to comply with the regulation.

The last engine load at the experiments was 10 bar IMEP_g. It was 50% of the maximum engine load and represents 75-80% of the maximum speed of a ship. The sensitivity of the combustion event to the fuel injection parameters at the single injection and the split injection strategies were investigated.

The effect of the SOI sweep on the combustion event was investigated by using the single injection strategy. The SOI timings were -7°CA, -5°CA, and -2°CA. The results of the SOI timing sweep investigation were the combustion event was retarded, the maximum in-cylinder pressure reduced, the combustion event was longer, the maximum PRR was lower, and NO_X emission decreased when the other emissions remained constant with the retarded SOI timing. Low in-cylinder temperature and cold cylinder walls at the low load operation of the engine allow using advanced SOI timing. The in-cylinder temperature and cylinder wall temperature are higher at higher engine loads. As a consequence, the SOI timing has to be closer to the TDC to prevent high PRR which can be dangerous for the engine.

The first injection timing sweep, the second injection timing sweep, the first injection duration sweep, and the rail pressure sweep were done by using the split injection strategy. The first injection timing sweep from -23°CA to -17°CA did not control the main combustion event timing and the combustion intensity. The combustion speed was higher, the ignition delay was shorter and maximum PRR was slightly higher with the retarded first injection timing. The second injection timing sweep from -8°CA to -2°CA has control over the main combustion event. The behavior of the second injection timing was the same as the SOI timing sweep at the single injection strategy. The first injection duration sweep from 22% to 10% had little effect on the combustion event. The maximum PRR and the NO_X emission decreased slightly. The rail pressure sweep from 1000 bar to 1400 bar had an influence on the combustion event. The combustion duration was shorter, the maximum PRR was higher, and the CO emission was lower with a higher rail pressure. General findings of the 10 bar

IMEP_g engine load are the thermodynamic efficiency was between 0.46 and 0.47, and the combustion efficiency was above 0.99. The CO and THC emissions were low and the NO_X emission was in the range of the IMO Tier II Limit.

Instead of doing experiments above 10 bar IMEP_g, the prediction was made by using gathered data of the SFC, engine efficiencies, and emissions until 10 bar IMEP_g and the curve fitting up to 16 bar IMEP_g was applied to these data. It was found that the SFC was the lowest with 381 g/kWh at 16 bar IMEP_g engine load. The combustion efficiency was above 0.99 until 16 bar IMEP_g and the highest thermodynamic efficiency was 0.485 at 16 bar IMEP_g. The CO_2 emission, which is related to the SFC and the engine efficiency, had the lowest value of 524 g/kWh at 16 bar IMEP_g. The CO and THC emissions were constant at 0.2 g/kWh from 10 bar IMEP_g until 16 bar IMEP_g. The NO_X emissions were in the range of the IMO Tier III Limit until 5.5 bar IMEP_g and in the range of the IMO Tier II Limit until 13.5 bar IMEP_g. After that engine load, it was above the IMO Tier II Limit. But this study was done without EGR, and it was experienced at the previous studies that the EGR can be used easily during the methanol PPC concept. The EGR up to 50% can reduce the NO_X emissions below 0.4 g/kWh without increasing CO_2, CO or PM emissions. The advantage of a lower stoichiometric air/fuel ratio of 6.45, when it compared with the diesel combustion, methanol can tolerate the excessive amount of EGR level. In addition to this, close to zero PM emissions of the methanol combustion and sulfur-free structure of methanol are the other advantages of this alternative fuel.

6.1.3 Final comments about the thesis study

The thesis study showed that the assessment model can evaluate alternative fuels from the various aspects of the maritime sector and can give an idea to the decision-makers who select alternative fuels for ships. The results of the assessment model and the commercial applications are in parallel. LNG has the highest point in the assessment model and it has the highest ship number worldwide. Methanol is the second alternative fuel in the assessment model and there are various fuel-cell applications and some applications as fuel on commercial ships, and high interest from the researchers worldwide. The third alternative fuel is ammonia in the assessment model. It has been used at the and the SCR for the NO_X abatement technology for many years. Also, nowadays, engine manufacturers have been working on using ammonia at their engines. These correspondences prove that the assessment model structure was well-prepared and the criteria weightings are appropriate to evaluate the alternative fuels for shipboard usage.

The experimental part proved that the methanol PPC can be used on ships at the near-coastal navigation areas which are risky for navigation. There were not any combustion stability problems from the low load to the medium load of the engine. The engine efficiency was high at all operating load range, especially for the loads from 10% to 25% engine load, it was between 43% and 48% and higher than the conventional diesel combustion. The previous study showed that the low load operation was between 24% and 32% at marine gas oil operation from 10% to 25% engine load. In addition to this, the SFC decreased from 347 g/kWh to 262 g/kWh from 10% to 25% engine load for the marine gas oil operation (Zincir et al., 2019b) while it reduced from 435 g/kWh to 411 g/kWh from 10% to 25% engine load at the thesis study. The emissions are the important advantage of the methanol PPC concept. In the same study, the CO_2 emissions were between 1112 g/kWh and 841 g/kWh from 10% to 25% engine load. The CO_2 emissions at the thesis study were between 584 g/kWh and 520 g/kWh from 10% to 25% engine load which is related to the lower carbon content of methanol and higher engine efficiency. The sulfur-free structure of methanol eliminates the SO_X formation. The short-chain structure of methanol and the combustion type of PPC concept resulted in almost zero PM emissions. On the other hand, the calculations by using empirical equations showed that the marine gas oil operation emitted SO_X emission from 0.9 g/kWh to 0.7 g/kWh and PM emissions from 0.3 g/kWh to 0.1 g/kWh between 10% and 25% engine loads. The CO emissions were 38 g/kWh at 10% engine load and decreased to 0.2 g/kWh at 25% engine load at the thesis study, but they were 8.5 g/kWh and 3.5 g/kWh at the same engine loads, respectively, for the marine gas oil operation. The THC emissions were almost the same for both methanol and marine gas oil operations (Zincir et al., 2019b). The NO_X emissions complied with the IMO Tier III Limits at the low load and low to medium load operation, and comply with the IMO Tier II Limits at the medium loads. The possibility of using an excessive amount of EGR without decreasing engine efficiency, increasing the SFC and CO_2 emission are advantages of the methanol PPC concept when it is compared with the conventional diesel combustion. On contrary, the NO_X emissions of marine gas oil operation at

10% to 25% engine load, were between 14.4 g/kWh and 11.5 g/kWh which did not even comply with the IMO Tier II Limits (Zincir et al., 2019b). Finally, the methanol PPC concept can be a fuel-combustion concept combination on ships to reduce CO_2 emissions, comply with the IMO 2020 Sulfur Cap and the NO_X Tier III Limit.

Instead of using methanol produced from natural gas or coal, bio-methanol is an option for the future. This type of methanol is produced from the biogenic feedstocks. Also, methanol can be produced by electricity from renewable energies and carbon capture technique or waste CO_2. Methanol produced from this type is named as electrofuel. These types of methanol are carbon-neutral fuels and they do not emit extra CO_2 emission to the atmosphere. It is a good solution to stricter CO_2 emission for the shipping sector in the future.

The further experimental study can be extending the operation range of the engine by using the methanol PPC concept to observe the combustion properties, engine performance and engine emissions at higher loads of the engine and formation of detailed engine operating map from the low load to high load operation of the methanol PPC.

6.2 Limitations of the Thesis Study

The limitations of the thesis study for the assessment model part and the experimental study part are listed below:

- The first limitation for the assessment model was finding alternative fuel experts in the maritime sector to get their opinions for the main criteria and the sub-criteria weightings.
- It was difficult to get a response from the experts because they were busy or did not intend to fill the point matrix.
- The weightings of the main criteria and the sub-criteria depended on expert opinions which are relatively subjective, and the weightings can be changed with the different expert opinions. For this reason, a sensitivity analysis of the main criteria weightings was done to test the reliability of the constituted assessment model. To observe the effect of the changes in the main criteria weightings on the order of the alternative fuels, 25% of weighting was added to each criterion

one by one for the different scenarios. After then 25% of weighting was deducted to each criterion one by one for the different scenarios. Lastly, the weightings of each criterion were made equal. Table 6.1 shows the new weightings of the main criteria in various scenarios. And then, the total performance weightings of the alternative fuels were calculated for the new scenarios. Table 6.2 shows the new alternative fuel weightings in various scenarios.

Table 6.1 : Sensitivity analysis table of the main criteria weightings.

	Main Criteria Weightings						
Scenarios	Safety	Legislation	Reliability	Technical	Economy	Ecology	Explanation
Base	0.346	0.146	0.090	0.025	0.046	0.346	N/A
I	0.433	0.127	0.078	0.022	0.040	0.300	Safety + 25%
II	0.331	0.183	0.086	0.024	0.044	0.331	Legislation + 25%
III	0.337	0.142	0.113	0.024	0.045	0.337	Reliability + 25%
IV	0.344	0.145	0.089	0.031	0.046	0.344	Technical + 25%
V	0.342	0.144	0.089	0.024	0.058	0.342	Economy + 25%
VI	0.300	0.127	0.078	0.022	0.040	0.433	Ecology + 25%
VII	0.260	0.165	0.102	0.028	0.052	0.392	Safety – 25%
VIII	0.361	0.110	0.094	0.026	0.048	0.361	Legislation – 25%
IX	0.354	0.150	0.068	0.026	0.047	0.354	Reliability – 25%
X	0.348	0.147	0.096	0.019	0.049	0.348	Technical – 25%
XI	0.350	0.148	0.091	0.028	0.035	0.350	Economy – 25%
XII	0.392	0.165	0.102	0.028	0.052	0.260	Ecology – 25%
XIII	0.167	0.167	0.167	0.167	0.167	0.167	Equal

Table 6.2 : Sensitivity analysis table of the alternative fuel weightings.

	Alternative Fuel Weightings						
Scenarios	Ammonia	Ethanol	Hydrogen	Kerosene	LNG	LPG	Methanol
Base	0.148	0.143	0.146	0.065	0.234	0.112	0.151
I	0.162	0.151	0.137	0.069	0.216	0.121	0.145
II	0.150	0.145	0.148	0.063	0.232	0.108	0.153
III	0.145	0.141	0.143	0.067	0.234	0.112	0.156
IV	0.148	0.143	0.145	0.066	0.234	0.112	0.151
V	0.147	0.143	0.145	0.065	0.236	0.113	0.150
VI	0.136	0.139	0.159	0.059	0.251	0.104	0.153
VII	0.134	0.136	0.155	0.061	0.252	0.103	0.158
VIII	0.146	0.142	0.144	0.067	0.236	0.116	0.150
IX	0.151	0.146	0.148	0.063	0.233	0.111	0.147
X	0.148	0.144	0.147	0.065	0.237	0.112	0.154
XI	0.149	0.144	0.147	0.065	0.233	0.111	0.153
XII	0.159	0.148	0.133	0.071	0.218	0.120	0.150
XIII	0.131	0.116	0.110	0.094	0.259	0.142	0.149

The plots of the alternative fuel weightings at various scenarios were shown in Figure 6.1. The scenario XIII is an extreme scenario with equal weightings, as a consequence, it affects the order of the alternative fuel more than the other scenarios. But the remaining scenarios show that the order of LNG, LPG, and kerosene does not change with the change of the weightings.

The orders of the methanol and ammonia fuel are affected slightly by the change of the weightings, due to the closer weightings of these alternative fuels. The sensitivity analysis showed that the constituted assessment model was a reliable model.

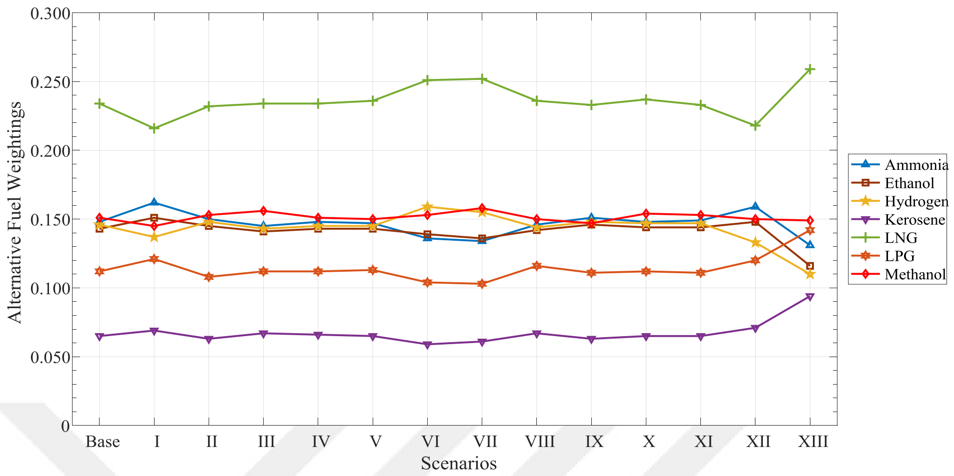

Figure 6.1: Alternative fuel weightings for different scenarios.

- At some main criteria and sub-criteria, it was difficult to change the qualitative information of the alternative fuels to the quantitative data for the pair-wise comparison.
- The criteria number and the criteria variation can affect the assessment. By using a different number or different type of criteria than the used ones, the assessment result can be changed.
- The engine was able to be operated up to 10 bar IMEP$_g$. The overheating problem of the engine limited the operating range and the experimental study could not be done beyond that engine load.
- The designated laboratory schedule for the experimental study was short to fix the engine problems or doing more experiments at various operating conditions.

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APPENDICES

APPENDIX A: Tables

APPENDIX A

Table A.1: Survey points of the main criteria.

Exper Number	Safety	Legislation	Reliability	Technical	Economy	Ecology
E1	5	5	4	3	4	3
E2	5	3	4	2	4	5
E3	4	3	5	3	2	5
E4	5	4	4	3	2	5
E5	5	5	4	2	3	5
E6	5	3	4	3	4	5
E7	5	5	4	4	3	4
E8	5	5	4	4	4	5
E9	5	3	2	5	4	4
E10	3	4	4	3	5	4
E11	5	5	5	5	4	4
E12	2	4	5	4	5	5
E13	5	5	4	4	5	5
E14	5	5	4	4	4	5
Total	64	59	57	49	53	64

Table A.2: Highest difference and pair-wise comparison interval of the main criteria.

Main Criteria	Points	Highest Difference	Pair-wise Comparison Interval
Safety	64	15.00	1.67
Ecology	64		
Legislation	59		
Reliability	57		
Economy	53		
Technical	49		

Table A.3: Pair-wise comparison points of the main criteria according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 1.67	1
1.67 – 3.34	2
3.34 – 5.01	3
5.01 – 6.68	4
6.68 – 8.35	5
8.35 – 10.02	6
10.02 – 11.69	7
11.69 – 13.36	8
13.36 – 15.00	9

Table A.4: Main criteria differences and pair-wise comparison points.

	Safety	Ecology	Legislation	Reliability	Economy	Technical
Safety	0 (1)	0 (1)	5 (3)	7 (5)	11 (7)	15 (9)
Ecology	-	0 (1)	5 (3)	7 (5)	11 (7)	15 (9)
Legislation	-	-	0 (1)	2 (2)	6 (4)	10 (6)
Reliability	-	-	-	0 (1)	4 (3)	8 (5)
Economy	-	-	-	-	0 (1)	4 (3)
Technical	-	-	-	-	-	0 (1)

Table A.5: Highest difference and pair-wise comparison interval of the technical criteria.

Technical Criteria	Points	Highest Difference	Pair-wise Comparison Interval
Effect on Engine components	58	10.00	1.11
Adaptability to Ships	55		
System Complexity	48		

Table A.6: Pair-wise comparison points of the technical criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 1.11	1
1.11 – 2.22	2
2.22 – 3.33	3
3.33 – 4.44	4
4.44 – 5.55	5
5.55 – 6.66	6
6.66 – 7.77	7
7.77 – 8.88	8
8.88 – 10.00	9

Table A.7: The technical criterion differences and pair-wise comparison points.

	Effect on Engine Components	Adaptability to Ships	System Complexity
Effect on Engine Components	0 (1)	3 (3)	10 (9)
Adaptability to Ships	-	0 (1)	7 (7)
System Complexity	-	-	0 (1)

Table A.8: Highest difference and pair-wise comparison interval of the economy criteria.

Economy Criteria	Points	Highest Difference	Pair-wise Comparison Interval
Fuel Cost	65	16.00	1.78
Commercial Effect	51		
Maintenance Cost	51		
Investment Cost	49		

Table A.9: Pair-wise comparison points of the economy criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 1.78	1
1.78 – 3.56	2
3.56 – 5.34	3
5.34 – 7.12	4
7.12 – 8.90	5
8.90 – 10.68	6
10.68 – 12.46	7
12.46 – 14.24	8
14.24 – 16.00	9

Table A.10: The economy criterion differences and pair-wise comparison points.

	Fuel Cost	Commercial Effect	Maintenance Cost	Investment Cost
Fuel Cost	0 (1)	14 (8)	14 (8)	16 (9)
Commercial Effect	-	0 (1)	0 (1)	2 (2)
Maintenance Cost	-	-	0 (1)	2 (2)
Investment Cost	-	-	-	0 (1)

Table A.11: Highest difference and pair-wise comparison interval of the alternative fuels at the flashpoint sub-criterion.

Alternative Fuels	Flashpoint	Highest Difference	Pair-wise Comparison Interval
Ammonia	132	320.00	35.60
Kerosene	38		
Ethanol	13		
Methanol	12		
LPG	-105		
Hydrogen	-150		
LNG	-188		

Table A.12: Pair-wise comparison points of the alternative fuels at the flashpoint sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 35.60	1
35.60 – 71.20	2
71.20 – 106.80	3
106.80 – 142.40	4
142.40 – 178.00	5
178.00 – 213.60	6
213.60 – 249.20	7
249.20 – 284.80	8
284.80 – 320.00	9

Table A.13: The flashpoint sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Ammonia	Kerosene	Ethanol	Methanol	LPG	Hydrogen	LNG
Ammonia	0 (1)	94 (3)	119 (4)	120 (4)	237 (7)	282 (8)	320 (9)
Kerosene	-	0 (1)	25 (1)	26 (1)	143 (5)	188 (6)	226 (7)
Ethanol	-	-	0 (1)	1 (1)	118 (4)	163 (5)	201 (6)
Methanol	-	-	-	0 (1)	117 (4)	162 (5)	200 (6)
LPG	-	-	-	-	0 (1)	45 (2)	83 (3)
Hydrogen	-	-	-	-	-	0 (1)	38 (2)
LNG	-	-	-	-	-	-	0 (1)

Table A.14: Highest difference and pair-wise comparison interval of the alternative fuels at the auto-ignition sub-criterion.

Alternative Fuels	Auto-ignition	Highest Difference	Pair-wise Comparison Interval
Ammonia	650	440.00	48.90
Hydrogen	585		
LNG	537		
Methanol	470		
LPG	450		
Ethanol	363		
Kerosene	210		

Table A.15: Pair-wise comparison points of the alternative fuels at the auto-ignition sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 48.90	1
48.90 – 97.80	2
97.80 – 146.70	3
146.70 – 195.60	4
195.60 – 244.50	5
244.50 – 293.40	6
293.40 – 342.30	7
342.30 – 391.20	8
391.20 – 440.00	9

Table A.16: The auto-ignition sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Ammonia	Hydrogen	LNG	Methanol	LPG	Ethanol	Kerosene
Ammonia	0 (1)	65 (2)	113 (3)	180 (4)	200 (5)	287 (6)	440 (9)
Hydrogen	-	0 (1)	48 (1)	115 (3)	135 (3)	222 (5)	375 (8)
LNG	-	-	0 (1)	67 (2)	87 (2)	174 (4)	327 (7)
Methanol	-	-	-	0 (1)	20 (1)	107 (3)	260 (6)
LPG	-	-	-	-	0 (1)	87 (2)	240 (5)
Ethanol	-	-	-	-	-	0 (1)	153 (4)
Kerosene	-	-	-	-	-	-	0 (1)

Table A.17: Highest difference and pair-wise comparison interval of the alternative fuels at the LEL sub-criterion.

Alternative Fuels	LEL	Highest Difference	Pair-wise Comparison Interval
Ammonia	15	14.30	1.60
Methanol	6		
LNG	5		
Hydrogen	4		
Ethanol	3.3		
LPG	2		
Kerosene	0.7		

Table A.18: Pair-wise comparison points of the alternative fuels at the LEL sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 1.60	1
1.60 – 3.20	2
3.20 – 4.80	3
4.80 – 6.40	4
6.40 – 8.00	5
8.00 – 9.60	6
9.60 – 11.20	7
11.20 – 12.80	8
12.80 – 14.30	9

Table A.19: The LEL sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Ammonia	Methanol	LNG	Hydrogen	Ethanol	LPG	Kerosene
Ammonia	0 (1)	9 (6)	10 (7)	11 (7)	11.7 (8)	13 (9)	14.3 (9)
Methanol	-	0 (1)	1 (1)	2 (2)	2.7 (2)	4 (3)	5.3 (4)
LNG	-	-	0 (1)	1 (1)	1.7 (2)	3 (2)	4.3 (3)
Hydrogen	-	-	-	0 (1)	0.7 (1)	2 (2)	3.3 (3)
Ethanol	-	-	-	-	0 (1)	1.3 (1)	2.6 (2)
LPG	-	-	-	-	-	0 (1)	1.3 (1)
Kerosene	-	-	-	-	-	-	0 (1)

Table A.20: Highest difference and pair-wise comparison interval of the alternative fuels at the UEL sub-criterion.

Alternative Fuels	UEL	Highest Difference	Pair-wise Comparison Interval
Kerosene	7	68.00	7.60
LPG	10		
LNG	15		
Ethanol	19		
Ammonia	25		
Methanol	36.5		
Hydrogen	75		

Table A.21: Pair-wise comparison points of the alternative fuels at the UEL sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 7.60	1
7.60 – 15.20	2
15.20 – 22.80	3
22.80 – 30.40	4
30.40 – 38.00	5
38.00 – 45.60	6
45.60 – 53.20	7
53.20 – 60.80	8
60.80 – 68.00	9

Table A.22: The UEL sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Kerosene	LPG	LNG	Ethanol	Ammonia	Methanol	Hydrogen
Kerosene	0 (1)	3 (1)	8 (2)	12 (2)	18 (3)	29.5 (4)	68 (9)
LPG	-	0 (1)	5 (1)	9 (2)	15 (2)	26.5 (4)	65 (9)
LNG	-	-	0 (1)	4 (1)	10 (2)	21.5 (3)	60 (8)
Ethanol	-	-	-	0 (1)	6 (1)	17.5 (3)	56 (8)
Ammonia	-	-	-	-	0 (1)	11.5 (2)	50 (7)
Methanol	-	-	-	-	-	0 (1)	38.5 (6)
Hydrogen	-	-	-	-	-	-	0 (1)

Table A.23: Highest difference and pair-wise comparison interval of the alternative fuels at the flame speed sub-criterion.

Alternative Fuels	Flame Speed	Highest Difference	Pair-wise Comparison Interval
Ammonia	14	256.00	28.40
LNG	38		
LPG	40		
Ethanol	41		
Methanol	50		
Kerosene	60		
Hydrogen	270		

Table A.24: Pair-wise comparison points of the alternative fuels at the flame speed sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 28.40	1
28.40 – 56.80	2
56.80 – 85.20	3
85.20 – 113.60	4
113.60 – 142.00	5
142.00 – 170.40	6
170.40 – 198.80	7
198.80 – 227.20	8
227.20 – 256.00	9

Table A.25: The flame speed sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Ammonia	LNG	LPG	Ethanol	Methanol	Kerosene	Hydrogen
Ammonia	0 (1)	24 (1)	26 (1)	27 (1)	36 (2)	46 (2)	256 (9)
LNG	-	0 (1)	2 (1)	3 (1)	12 (1)	22 (1)	232 (9)
LPG	-	-	0 (1)	1 (1)	10 (1)	20 (1)	230 (9)
Ethanol	-	-	-	0 (1)	9 (1)	19 (1)	229 (9)
Methanol	-	-	-	-	0 (1)	10 (1)	220 (8)
Kerosene	-	-	-	-	-	0 (1)	210 (8)
Hydrogen	-	-	-	-	-	-	0 (1)

Table A.26: Highest difference and pair-wise comparison interval of the alternative fuels at the exposure rate sub-criterion.

Alternative Fuels	Exposure Rate	Highest Difference	Pair-wise Comparison Interval
Ethanol	1900	1883.00	209.20
LPG	1900		
LNG	650		
Hydrogen	336		
Kerosene	200		
Methanol	196		
Ammonia	17		

Table A.27: Pair-wise comparison points of the alternative fuels at the exposure rate sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 209.20	1
209.20 – 418.40	2
418.40 – 627.60	3
627.60 – 836.80	4
836.80 – 1046.00	5
1046.00 – 1255.20	6
1255.20 – 1464.40	7
1464.40 – 1673.60	8
1673.60 – 1883.00	9

Table A.28: The exposure rate sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Ethanol	LPG	LNG	Hydrogen	Kerosene	Methanol	Ammonia
Ethanol	0 (1)	0 (1)	1250 (6)	1564 (8)	1700 (9)	1704 (9)	1883 (9)
LPG	-	0 (1)	1250 (6)	1564 (8)	1700 (9)	1704 (9)	1883 (9)
LNG	-	-	0 (1)	314 (2)	450 (3)	454 (3)	633 (4)
Hydrogen	-	-	-	0 (1)	136 (1)	140 (1)	319 (2)
Kerosene	-	-	-	-	0 (1)	4 (1)	183 (1)
Methanol	-	-	-	-	-	0 (1)	179 (1)
Ammonia	-	-	-	-	-	-	0 (1)

Table A.29: Highest difference and pair-wise comparison interval of the alternative fuels at the legislation criterion.

Alternative Fuels	Legislation	Highest Difference	Pair-wise Comparison Interval
LNG	71	49.00	5.44
Ammonia	70		
Methanol	69		
Ethanol	67		
Hydrogen	67		
Kerosene	27		
LPG	22		

Table A.30: Pair-wise comparison points of the alternative fuels at the legislation criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 5.44	1
5.44 – 10.88	2
10.88 – 16.32	3
16.32 – 21.76	4
21.76 – 27.20	5
27.20 – 32.64	6
32.64 – 38.08	7
38.08 – 43.52	8
43.52 – 49.00	9

Table A.31: The legislation criterion differences and pair-wise comparison points of the alternative fuels.

	LNG	Ammonia	Methanol	Ethanol	Hydrogen	Kerosene	LPG
LNG	0 (1)	1 (1)	2 (1)	4 (1)	4 (1)	44 (9)	49 (9)
Ammonia	-	0 (1)	1 (1)	3 (1)	3 (1)	43 (8)	48 (9)
Methanol	-	-	0 (1)	2 (1)	2 (1)	42 (8)	47 (9)
Ethanol	-	-	-	0 (1)	0 (1)	40 (8)	45 (9)
Hydrogen	-	-	-	-	0 (1)	40 (8)	45 (9)
Kerosene	-	-	-	-	-	0 (1)	5 (1)
LPG	-	-	-	-	-	-	0 (1)

Table A.32: Highest difference and pair-wise comparison interval of the alternative fuels at the maturity sub-criterion.

Alternative Fuels	Maturity	Highest Difference	Pair-wise Comparison Interval
LNG	5	3.00	0.33
LPG	4		
Methanol	4		
Ethanol	3		
Hydrogen	3		
Kerosene	2		
Ammonia	2		

Table A.33: Pair-wise comparison points of the alternative fuels at the maturity sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 0.33	1
0.33 – 0.66	2
0.66 – 0.99	3
0.99 – 1.32	4
1.32 – 1.65	5
1.65 – 1.98	6
1.98 – 2.31	7
2.31 – 2.64	8
2.64 – 3.00	9

Table A.34: The maturity sub-criterion differences and pair-wise comparison points of the alternative fuels.

	LNG	LPG	Methanol	Ethanol	Hydrogen	Kerosene	Ammonia
LNG	0 (1)	1 (4)	1 (4)	2 (7)	2 (7)	3 (9)	3 (9)
LPG	-	0 (1)	0 (1)	1 (4)	1 (4)	2 (7)	2 (7)
Methanol	-	-	0 (1)	1 (4)	1 (4)	2 (7)	2 (7)
Ethanol	-	-	-	0 (1)	0 (1)	1 (4)	1 (4)
Hydrogen	-	-	-	-	0 (1)	1 (4)	1 (4)
Kerosene	-	-	-	-	-	0 (1)	0 (1)
Ammonia	-	-	-	-	-	-	0 (1)

Table A.35: Highest difference and pair-wise comparison interval of the alternative fuels at the bunkering capability sub-criterion.

Alternative Fuels	Bunkering Capability	Highest Difference	Pair-wise Comparison Interval
Methanol	13	7.00	0.78
Kerosene	11		
LNG	9		
LPG	9		
Ammonia	7		
Ethanol	6		
Hydrogen	6		

Table A.36: Pair-wise comparison points of the alternative fuels at the bunkering capability sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 0.78	1
0.78 – 1.56	2
1.56 – 2.34	3
2.34 – 3.12	4
3.12 – 3.90	5
3.90 – 4.68	6
4.68 – 5.46	7
5.46 – 6.24	8
6.24 – 7.00	9

Table A.37: The bunkering capability sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Methanol	Kerosene	LNG	LPG	Ammonia	Ethanol	Hydrogen
Methanol	0 (1)	2 (3)	4 (6)	4 (6)	6 (8)	7 (9)	7 (9)
Kerosene	-	0 (1)	2 (3)	2 (3)	4 (6)	5 (7)	5 (7)
LNG	-	-	0 (1)	0 (1)	2 (3)	3 (4)	3 (4)
LPG	-	-	-	0 (1)	2 (3)	3 (4)	3 (4)
Ammonia	-	-	-	-	0 (1)	1 (2)	1 (2)
Ethanol	-	-	-	-	-	0 (1)	0 (1)
Hydrogen	-	-	-	-	-	-	0 (1)

Table A.38: Highest difference and pair-wise comparison interval of the alternative fuels at the system complexity sub-criterion.

Alternative Fuels	System Complexity	Highest Difference	Pair-wise Comparison Interval
Kerosene	12	6.00	0.67
Ethanol	9		
Methanol	9		
Ammonia	6		
Hydrogen	6		
LNG	6		
LPG	6		

Table A.39: Pair-wise comparison points of the alternative fuels at the system complexity sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 0.67	1
0.67 – 1.34	2
1.34 – 2.01	3
2.01 – 2.68	4
2.68 – 3.35	5
3.35 – 4.02	6
4.02 – 4.69	7
4.69 – 5.36	8
5.36 – 6.00	9

Table A.40: The system complexity sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Kerosene	Ethanol	Methanol	Ammonia	Hydrogen	LNG	LPG
Kerosene	0 (1)	3 (5)	3 (5)	6 (9)	6 (9)	6 (9)	6 (9)
Ethanol	-	0 (1)	0 (1)	3 (5)	3 (5)	3 (5)	3 (5)
Methanol	-	-	0 (1)	3 (5)	3 (5)	3 (5)	3 (5)
Ammonia	-	-	-	0 (1)	0 (1)	0 (1)	0 (1)
Hydrogen	-	-	-	-	0 (1)	0 (1)	0 (1)
LNG	-	-	-	-	-	0 (1)	0 (1)
LPG	-	-	-	-	-	-	0 (1)

Table A.41: Highest difference and pair-wise comparison interval of the alternative fuels at the adaptability to ships sub-criterion.

Alternative Fuels	Adaptability to Ships	Highest Difference	Pair-wise Comparison Interval
Kerosene	8	6.00	0.67
Ethanol	4		
Methanol	4		
Ammonia	2		
Hydrogen	2		
LNG	2		
LPG	2		

Table A.42: Pair-wise comparison points of the alternative fuels at the adaptability to ships sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 0.67	1
0.67 – 1.34	2
1.34 – 2.01	3
2.01 – 2.68	4
2.68 – 3.35	5
3.35 – 4.02	6
4.02 – 4.69	7
4.69 – 5.36	8
5.36 – 6.00	9

Table A.43: The adaptability to ships sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Kerosene	Ethanol	Methanol	Ammonia	Hydrogen	LNG	LPG
Kerosene	0 (1)	4 (6)	4 (6)	6 (9)	6 (9)	6 (9)	6 (9)
Ethanol	-	0 (1)	0 (1)	2 (3)	2 (3)	2 (3)	2 (3)
Methanol	-	-	0 (1)	2 (3)	2 (3)	2 (3)	2 (3)
Ammonia	-	-	-	0 (1)	0 (1)	0 (1)	0 (1)
Hydrogen	-	-	-	-	0 (1)	0 (1)	0 (1)
LNG	-	-	-	-	-	0 (1)	0 (1)
LPG	-	-	-	-	-	-	0 (1)

Table A.44: Highest difference and pair-wise comparison interval of the alternative fuels at the effect on engine components sub-criterion.

Alternative Fuels	Effect on Engine Components	Highest Difference	Pair-wise Comparison Interval
Kerosene	7.0	7.00	0.78
Ethanol	6.0		
Methanol	6.0		
Hydrogen	5.8		
Ammonia	1.0		
LNG	0.0		
LPG	0.0		

Table A.45: Pair-wise comparison points of the alternative fuels at the effect on engine components sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 0.78	1
0.78 – 1.56	2
1.56 – 2.34	3
2.34 – 3.12	4
3.12 – 3.90	5
3.90 – 4.68	6
4.68 – 5.46	7
5.46 – 6.24	8
6.24 – 7.00	9

Table A.46: The effect on engine components sub-criterion differences and pair-wise comparison points of the alternative fuels.

	LNG	LPG	Ammonia	Hydrogen	Methanol	Ethanol	Kerosene
LNG	0 (1)	0 (1)	1 (2)	5.8 (8)	6 (8)	6 (8)	7 (9)
LPG	-	0 (1)	1 (2)	5.8 (8)	6 (8)	6 (8)	7 (9)
Ammonia	-	-	0 (1)	4.8 (7)	5 (7)	5 (7)	6 (8)
Hydrogen	-	-	-	0 (1)	0.2 (1)	0.2 (1)	1.2 (2)
Methanol	-	-	-	-	0 (1)	0 (1)	1 (2)
Ethanol	-	-	-	-	-	0 (1)	1 (2)
Kerosene	-	-	-	-	-	-	0 (1)

Table A.47: Highest difference and pair-wise comparison interval of the alternative fuels at the commercial effect sub-criterion.

Alternative Fuels	Commercial Effect (x1000)	Highest Difference	Pair-wise Comparison Interval
Kerosene	10	22.00	2.44
LPG	13		
Ethanol	15		
LNG	16		
Methanol	20		
Ammonia	25		
Hydrogen	32		

Table A.48: Pair-wise comparison points of the alternative fuels at the commercial effect sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 2.44	1
2.44 – 4.88	2
4.88 – 7.32	3
7.32 – 9.76	4
9.76 – 12.20	5
12.20 – 14.64	6
14.64 – 17.08	7
17.08 – 19.52	8
19.52 – 22.00	9

Table A.49: The commercial effect sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Kerosene	LPG	Ethanol	LNG	Methanol	Ammonia	Hydrogen
Kerosene	0 (1)	3 (2)	5 (3)	6 (3)	10 (5)	15 (7)	22 (9)
LPG	-	0 (1)	2 (1)	3 (2)	7 (3)	12 (5)	19 (8)
Ethanol	-	-	0 (1)	1 (1)	5 (3)	10 (5)	17 (7)
LNG	-	-	-	0 (1)	4 (2)	9 (4)	16 (7)
Methanol	-	-	-	-	0 (1)	5 (3)	12 (5)
Ammonia	-	-	-	-	-	0 (1)	7 (3)
Hydrogen	-	-	-	-	-	-	0 (1)

Table A.50: Highest difference and pair-wise comparison interval of the alternative fuels at the investment cost sub-criterion.

Alternative Fuels	Investment Cost (x10000)	Highest Difference	Pair-wise Comparison Interval
Ammonia	886	615.00	68.3
Ethanol	704		
LPG	617		
Kerosene	374		
Methanol	358		
LNG	340		
Hydrogen	271		

Table A.51: Pair-wise comparison points of the alternative fuels at the investment cost sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 68.30	1
68.30 – 136.60	2
136.60 – 204.90	3
204.90 – 273.20	4
273.20 – 341.50	5
341.50 – 409.80	6
409.80 – 478.10	7
478.10 – 546.40	8
546.40 – 615.00	9

Table A.52: The investment cost sub-criterion differences and pair-wise comparison points of the alternative fuels.

	Ammonia	Ethanol	LPG	Kerosene	Methanol	LNG	Hydrogen
Ammonia	0 (1)	182 (3)	269 (4)	512 (8)	528 (8)	546 (8)	615 (9)
Ethanol	-	0 (1)	87 (2)	330 (5)	346 (6)	364 (6)	433 (7)
LPG	-	-	0 (1)	243 (4)	259 (4)	277 (5)	346 (6)
Kerosene	-	-	-	0 (1)	16 (1)	34 (1)	103 (2)
Methanol	-	-	-	-	0 (1)	18 (1)	87 (2)
LNG	-	-	-	-	-	0 (1)	69 (2)
Hydrogen	-	-	-	-	-	-	0 (1)

Table A.53: Highest difference and pair-wise comparison interval of the alternative fuels at the maintenance cost sub-criterion.

Alternative Fuels	Maintenance Cost (x1000)	Highest Difference	Pair-wise Comparison Interval
LNG	220	203.00	22.56
LPG	220		
Ammonia	156		
Hydrogen	38		
Ethanol	29		
Methanol	29		
Kerosene	17		

Table A.54: Pair-wise comparison points of the alternative fuels at the maintenance cost sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 22.56	1
22.56 – 45.12	2
45.12 – 67.68	3
67.68 – 90.24	4
90.24 – 112.80	5
112.80 – 135.36	6
135.36 – 157.92	7
157.92 – 180.48	8
180.48 – 203.00	9

Table A.55: The maintenance cost sub-criterion differences and pair-wise comparison points of the alternative fuels.

	LNG	LPG	Ammonia	Hydrogen	Ethanol	Methanol	Kerosene
LNG	0 (1)	0 (1)	64 (3)	182 (9)	191 (9)	191 (9)	203 (9)
LPG	-	0 (1)	64 (3)	182 (9)	191 (9)	191 (9)	203 (9)
Ammonia	-	-	0 (1)	118 (6)	127 (6)	127 (6)	139 (7)
Hydrogen	-	-	-	0 (1)	9 (1)	9 (1)	21 (1)
Ethanol	-	-	-	-	0 (1)	0 (1)	12 (1)
Methanol	-	-	-	-	-	0 (1)	12 (1)
Kerosene	-	-	-	-	-	-	0 (1)

Table A.56: Highest difference and pair-wise comparison interval of the alternative fuels at the fuel cost sub-criterion.

Alternative Fuels	Fuel Cost	Highest Difference	Pair-wise Comparison Interval
LNG	2.266	1.693	0.188
LPG	1.558		
Hydrogen	0.966		
Kerosene	0.823		
Ethanol	0.801		
Ammonia	0.726		
Methanol	0.573		

Table A.57: Pair-wise comparison points of the alternative fuels at the fuel cost sub-criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 0.188	1
0.188 – 0.376	2
0.376 – 0.564	3
0.564 – 0.752	4
0.752 – 0.940	5
0.940 – 1.128	6
1.128 – 1.316	7
1.316 – 1.504	8
1.504 – 1.693	9

Table A.58: The fuel cost sub-criterion differences and pair-wise comparison points of the alternative fuels.

	LNG	LPG	Hydrogen	Kerosene	Ethanol	Ammonia	Methanol
LNG	0 (1)	0.708 (4)	1.300 (7)	1.443 (8)	1.465 (8)	1.540 (9)	1.693 (9)
LPG	-	0 (1)	0.592 (4)	0.735 (4)	0.757 (5)	0.832 (5)	0.985 (6)
Hydrogen	-	-	0 (1)	0.143 (1)	0.165 (1)	0.240 (2)	0.393 (3)
Kerosene	-	-	-	0 (1)	0.022 (1)	0.097 (1)	0.250 (2)
Ethanol	-	-	-	-	0 (1)	0.075 (1)	0.228 (2)
Ammonia	-	-	-	-	-	0 (1)	0.153 (1)
Methanol	-	-	-	-	-	-	0 (1)

Table A.59: Highest difference and pair-wise comparison interval of the alternative fuels at the ecology criterion.

Alternative Fuels	Ecology	Highest Difference	Pair-wise Comparison Interval
LNG	35	16.00	1.78
Hydrogen	33		
Methanol	31		
Ethanol	29		
Ammonia	26		
LPG	25		
Kerosene	19		

Table A.60: Pair-wise comparison points of the alternative fuels at the ecology criterion according to the intervals.

Intervals	Pair-wise Comparison Points
0 – 1.78	1
1.78 – 3.56	2
3.56 – 5.34	3
5.34 – 7.12	4
7.12 – 8.90	5
8.90 – 10.68	6
10.68 – 12.46	7
12.46 – 14.24	8
14.24 – 16.00	9

Table A.61: The ecology criterion differences and pair-wise comparison points of the alternative fuels.

	LNG	Hydrogen	Methanol	Ethanol	Ammonia	LPG	Kerosene
LNG	0 (1)	2 (2)	4 (3)	6 (4)	9 (6)	10 (6)	16 (9)
Hydrogen	-	0 (1)	2 (2)	4 (3)	7 (4)	8 (5)	14 (8)
Methanol	-	-	0 (1)	2 (2)	5 (3)	6 (4)	12 (7)
Ethanol	-	-	-	0 (1)	3 (2)	4 (3)	10 (6)
Ammonia	-	-	-	-	0 (1)	1 (1)	7 (4)
LPG	-	-	-	-	-	0 (1)	6 (4)
Kerosene	-	-	-	-	-	-	0 (1)

CURRICULUM VITAE

Name Surname : Burak ZİNCİR

Place and Date of Birth : Üsküdar / 09.02.1988

E-Mail : bzincir@itu.edu.tr

EDUCATION :

- **B.Sc.** :2010, Istanbul Technical University, Maritime Faculty, Marine Engineering Department Dual Diploma Program

  2010, State University of New York, Maritime College, Marine Engineering Department
- **M.Sc.** :2014, Istanbul Technical University, Maritime Faculty, Maritime Transportation Engineering Department

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2010-2013 Superintendent at Seahorse Shipping & Engineering Co. Ltd.
- 2014 Completed Master Degree at Istanbul Technical University
- 2017 Academic Encouragement Reward
- 2019 Academic Encouragement Reward

PUBLICATIONS ON THE THESIS:

Journal Paper (SCI-Expanded)

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