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Index of Articles

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Research Paper

Relationship of Dangerous Behavior of Professional Drivers and Penalties on Accidents of Intercity Road Network

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Abstract

High rate of fatalities in road transportation has raised a world-wide effort to utilize appropriate strategies in order to reduce road accidents. In this regard professional drivers are of great concern due to their large size vehicles and high rate of passenger occupancy. Additionally, comparing to other users of network, planning for behavioral change among them is much more achievable due to their organizational and hence occupational dependency. This research proposes a validated questionnaire in order to measure the dangerous behavior of professional drivers of passenger cars, bus and trucks of intercity road network. Additionally, a structural equation model was developed that explored the causal relationship of dangerous behavior on accident. Further the model indicates that supervising drivers (through penalties) was able to mediate and indeed, reduce the effect of dangerous behavior on accidents previously experienced by respondents. In this study, Data collection was conducted among 603 drivers from 6th-21th September 2022, in Kermanshah, Iran. Results of this study suggests that behavioral change of drivers and adequate supervision on them reduce number of accidents on intercity road network.

Keywords: Professional drivers, Dangerous driving behavior, Road accident

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1. Introduction

Individual, vehicle, road, and environmental factors in a casual chain may result in fatalities in road traffic accidents. Sanchez-Mangas et. al. (2010) discussed that driving behavior and vehicle features are pre-collision factors, which determine the severity of the accident. Other factors including vehicle structure, restraint system, and protection equipment involved in accidents medical treatment affect the survival chance. Driving behavior which determine collision motion and level of damage (Ren, 2010) differs among drivers due to demographic factors, driving experience (Yan et. al. 2013) and also facilities and road characteristics (Pei, 2003).

Focusing on driving behavior among all, different scholars discussed it as a main contributor in road accidents (WHO, 2018; DGT, 2021). Risky behaviors such as exceeding speed limit are of high influencing factors which result in severe collision and human damage. Due to difficulties to explain human behavior (Megías-Robles et al., 2022) risk decision making models were applied to analyze human behavior in risky situations in previous studies (Navas et. al, 2019; Ventsislavova et. al.,2021) which have covered factors such as experience, motivation, memory, attention and learning (lerner et. al.,2015; Maldonado et. al., 2020; Pessoa, 2008).

Traffic in developing countries usually consists of different vehicle types with a variety of statistic and dynamic characteristics which occupy a same right of way. This becomes more serious in main roads connecting cities where freight transport has a greater share in comparison with urban transport. Hence, drivers of public transport and freight vehicles consisting of passenger cars (intercity taxi), buses and trucks gain special notice in safety policy making. A few reasons can be discussed in this regard: first; people usually expect professional drivers to drive in a defense mode. Because in addition to their class-1 driving license, professional drivers have to pass minimum requirements to get the permit to transfer cargo or passengers, so any mistake can treat their working permit. Therefore, they are required to avoid involvement in crashes. Second; passenger cars/buses are highly occupied and any collision may result in fatalities with a high rate. Third, trucks and buses with different characteristics and large size leave greater traffic effects. Fourth, any collision that a bus involves in can easily reduce public confidence and hence tendency for traveling by bus. This is in contrary with the general strategy of motivating people to use public transport instead of their private cars. And finally, professional drivers are more available to be monitored, supervised and trained in order to improve their driving behavior.

Based on the reason discussed above, this research focuses on evaluating the effect of dangerous behavior of professional drivers (bus, passenger car and truck drivers) on the number of accidents they have experienced during their professional driving. Additionally, the effects of supervising them which can change the tendency toward risk taking is also considered.

At the first step, an appropriate instrument was required to measure dangerous behavior as a latent variable. Different instruments in this regard were validated in previous scholars. For example, Mokarami et. al. (2019) developed two questionnaires; Driver Safety Culture Questionnaire (DSCQ) and; Public Transport Driver Behavior (PTDBQ). In their study, they measured two latent variables: organizational safety culture and unsafe behavior among urban bus drivers. Finally, the relationships of the two measured latent variable and number of accidents were explored through structural equation modelling. Another example is a study by Rowe et. al. (2022) in which the Early

Driving Development Questionnaire (EDD-Q) was validated for measuring safe behavior of new drivers. Bandyopadhyaya et. al. (2022) in their study developed a 27-item driver behavior questionnaire (DBQ) to measure long distance aberrations in a self-reporting process.

To our best knowledge, any study has not been yet conducted to measure the dangerous behavior of professional drivers in intercity road network. At the first glance, passenger car vs. buses, similar to passenger vs. freight vehicles may varies in their characteristics but the common issue among them is their organizational and hence occupational dependency. This creates a potential to offer appropriate suggestion for policy makers based on data and analytical process, for a concentrated effort under the shelter of organizational responsibilities and goals. Moreover, differences in urban and intercity network make dangerous behaviour different in the two networks. For example, while passing a red light is an important violation in urban network, there in so traffic light in intercity network. Overall, this research aims to validate an instrument to measure dangerous behavior of professional drivers in intercity network and further to explore the relationship of dangerous behavior and penalties on accidents that professional drivers involved previously. The hypothesis of the study is: 1- dangerous behavior increases accident involvement of drivers and 2- penalties (a combination of tickets and any organizational action which may be originated from public reports) could mediate the dangerous behavior effect on accident involvement.

Worth to mention that number of accidents as the dependent variable were previously predicted through structural equation models in several studies, by different exploratory variables such as ability emotional intelligence and risky driving (Megias-robels et. al., 2022), organizational safety culture and unsafe behavior (Mokarami et al., 2019) and self-reported aberrations (Bandyopadhyaya et. al., 2022).

Next section explains the methodology of the study. Result is reported in section 3 and further discussed in section 4. Finally, conclusion is presented and suggestions, application and future study are offered.

2. Method

2.1. Study Area

Data of present study was collected by meeting the respondents in fuel stations/TIR parks/ on way restaurants of the Kermanshah province, Iran. Kermanshah is located in the west of Iran. Road network (intercity) consists of different classes of roads as is reported in table 1.

Table 1. Length of different road types in Kermanshah

Type of road	Total Length (KM)
Highway	416.78
Main Road	522.95
Minor Road	1891.4
Rural	5151

Share of different classes of intercity road network of Kermanshah province is given in figure 1.

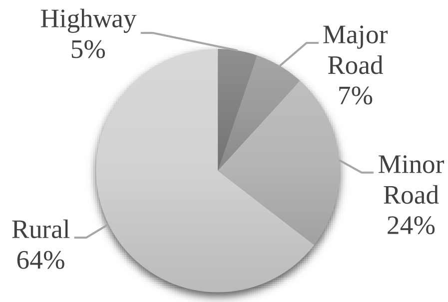

Figure 1. Share of different classes of intercity road network of Kermanshah province

Total length of highway plus main and minor road of Kermanshah rate it in 19th place among other 30 provinces of Iran.

Based on the report of the Iranian Legal Medicine Organization, 19.06 out of each 100000 people died due to road accidents in 2020. This value is 23.56 (intercity and urban) and 18.54 for intercity road accidents for Kermanshah province. In the intercity road network of Kermanshah, one person dies in each 22 hours and more than one person is injured in each 2 hours.

On the other hand, five border points at the west of Kermanshah pass freight and passenger to/from Iraq (or third party). This means that road network of this province not only serves the regular freight and passenger of the province but also play a national and international role in country transportation. This clarifies the importance of safety monitoring in this province.

It should be noted that, however data was collected in Kermanshah, drivers are not necessarily from Kermanshah or do not necessarily live in Kermanshah and are not limited to drive in this province. Hence a sort of generality can be claimed in the sampling process.

2.2. Participants

A community sample of 603 drivers participated in this study. Participants were bus, public passenger car and truck drivers with valid permit obtained from Road Maintenance and Transportation (RMTO). RMTO is the responsible organization of intercity transportation in Iran which issues the required permit for working as a professional driver in intercity road network. This organization also supervise and trains professional drivers as well. Meantime RMTO is responsible for intercity road transportation safety.

Of the total sample, 224 participants were passenger car drivers, 263 were truck drivers and the 116 remaining were bus drivers. All drivers were men aging from 27 to 61 years old (Mean=41.24, SD=12.08). It should be noted that 792 questionnaires were initially distributed of which 603 returned with less than 20% missing data. Respondents were divided into groups A and B including 302 and 301 members randomly. Results of t-test and χ^2-test confirmed no significant difference between the two groups. Data of group A was used for Exploratory Factor Analysis (EFA) and the results were confirmed by Confirmatory Factor Analysis (CFA) using data of group B. worth to mention that final analysis was accomplished applying the total data.

2.3. Data Collection Procedure and Measures

Data collection procedure was done in a 15-days period from 6th-21th September 2022. In different times of the day drivers who referred to Tir-parks/ fuel stations/ on way restaurants were randomly invited to respond the questionnaire. Participation was voluntary but participants were compensated with ice-cream and cookie. At the first part of the questionnaire age, time with permit from RMTO (in month), annual driving kilometer, number of accidents during professional driving, number of driving tickets, number of being complained by public or reprimanded by RMTO were asked. It should be explained that public are able to call 141 and report any violation and unsafe behavior of professional drivers to RMTO. RMTO on the other hand has legal right to penalize the offender driver. Hence, along with traffic tickets by the police, a total of three parts (public, RMTO and Police) supervise driver's behavior. Total number of "penalties" applied in next sections refers to any kind of penalty obtained by police or RMTO. Direct count of reports by public are not considered inhere for two reasons: first; it may lead to an action taken by RMTO and hence does not require to be counted independently. Second; public do not necessarily evaluate situations professionally and may make mistake in assessing violation of a driver. Hence, any action by RMTO, which may originate by public reports, are included in data as an adding number to "penalties".

Worth to mention that the severity of the accidents might be considered as dependent variable. This variable can be measured by adding up number of fatal/ injury/ damaging accidents each of which weighted by a proper weight. But this might mislead the results. For example, consider two scenarios: in the first scenario, exceeding speed limit consequent to collision to a pedestrian. In the second scenario, a similar dangerous behavior results in collision to another vehicle. In the first accident vulnerability of the pedestrian results in death but in the second scenario, safety equipment of the vehicle saves human lives. Though, other characteristics rather than dangerous behavior of the driver effect the result and severity of the accident and should not be ignored in the modelling process. The focus of this research is on causal relationship between dangerous behavior and occurrence of the collision regardless of severity of the accident. Thus, number of total accidents is considered.

Second part of the questionnaire aims to evaluate dangerous behavior of drivers. This part includes items suggested by a team consisting of 10 experts from RMTO, 12 police officers and 10 professional drivers. Items were designed in a chain of interview process and literature review. An initial list including 29 items was prepared. Response to each item was provided in a 5-point Likert scale from 1 (Never) to 5 (Always).

2.4. Validity and Reliability of the Instrument

Half of the police officers and RMTO experts reviewed the items for any grammatical/ wording problems and miss understandings. The other half were asked to assess Content Validity Index (CVI) and Content Validity Ratio (CVR) of the instrument. Inter-Class Correlation (ICC) was applied for checking the relevance of the items. Additionally internal consistency was evaluated by the Cronbach's α. Prior to EFA and CFA, Kasier-Mayer-Olkin (KMO) was assessed. PCA with a varimax rotation was next performed in order to determine the factors of the items. CFA was then applied to confirm dimensions of EFA. Finally, qualification of the measurement model was assessed by different fit indices, which are reported in next section.

2.5. Data Analysis

Following descriptive analysis, structural equation model (SEM) was applied to determine the relationships between variables. A series of multiple linear regression were tested to describe the causal relationship between latent variable and number of penalties with number of accidents divided by (Annual driving distance* Time with license from RMTO (year) as the dependent variable. Alternative indices performed to evaluate the modal fit.

Analysis was conducted using SPSS 27(IBM Corporation, USA) and IBM SPSS Amos 27.0 software.

3. Results

3.1. Descriptive Analysis

Descriptive analysis of demographic and occupational variables and Pearson's correlation with dependent variable are reported in table 2.

Table 2. Statistics of study variables

Variable	Mean	Standard Deviation	Pearson's correlation with dependent variable
Age (year)	41.24	12.08	-0.21**
Time with permit from RMTO (year)	15.24	4.75	0.32**
Annual driving distance(km)	71320	25710	0.35*
Number of penalties	3.25	1.92	0.28*
Dependent variable	1.87	1.34	-

*p<0.05, **p<0.01

As shown in table 2, age was negatively correlated with the dependent variable. This may happen because of inducing risk aversion among older drivers. However other variables were significantly positively correlated with number of variables. Positive correlation between number of penalties and the dependent variable suggests that drivers who involved more accidents, have been already penalized for their violations. However, continuing violation and dangerous behavior, along with the accidental and randomness nature of crashes, finally lead to more accidents during their professional driving.

3.2. Validity and Reliability of the Instrument

According to the Lawshe method (1975) CVR is required to be ≥0.62 and CVI is required to be greater than 0.75. Considering the result of CVI and CVR, a total of 21 items from the initial 29 items were qualified to remain in the instrument. The mean CVIs, mean CVRs of the measures were 0.83 and 0.72 respectively. ICC was 0.81, which falls in the range of 0.75 and 0.9 and hence reflects good reliability (Koo and LI, 2016).

Additionally, the result of Cronbach's α coefficient was 0.92 which revealed excellent internal consistency.

Moreover, KMO was 0.834 which confirmed the qualification of the data for factor analysis. Four factors with eigenvalues over 1 were revealed by EFA. The factors explained 54.7 percent of the total variance. Factors were named based on the content of the sub-items. It should be noted that 5 items were disqualified and removed. Next CFA confirmed the revealed factors. Results are shown in table 3. Figure 2 presents the structure of the analysis. Goodness-of-fit of the CFA was assessed by different indices namely comparative fit index (CFI), root mean square error of approximation (RMSEA), standardized root mean square residual (SRMR), results of which are reported in table 4.

3.3. Structural Equation Model

SEM was applied to explore the relationship between dangerous behavior and penalties with the dependent variable (number of accidents divided by (Annual driving distance* Time with license from RMTO (year)). A positive association between dangerous behavior and accident ($\beta=0.24$, $p<0.001$) was explored. In addition, while penalties showed a significant positive effect on accident, it significantly mediated the relationship between dangerous behavior and accidents. The structure of the model and standard coefficient and errors are shown in figure 3. Results of t-test confirmed the significance of the coefficient at 95% CI.

Table 3. Factor Analysis Result

Factor	Item	Variance explained	Correlation	Coronach's α
Driving violations	1. Exceed speed limit	24.17	0.623	0.83
	2. Crossing solid line		0.634	
	3. Sudden braking		0.601	
	4. Stopping/ parking in dangerous location		0.584	
Traffic interaction	5. Overtaking other vehicles	12.03	0.612	0.74
	6. Not-observing right-of-way of other vehicles		0.591	
	7. Using and blocking speed lane		0.603	
Spatial carelessness	8. Sudden lane change	10.79	0.574	0.71
	9. Deviation to left		0.593	
	10. Not observing safe distance from front/lateral vehicle		0.623	
Self-engagement	11. Driving while sleepy	7.71	0.674	0.68
	12. Using mobile cell		0.521	
	13. Arguing with another driver/ passengers/ co-driver		0.624	
	14. Talking to passengers/co-driver		0.631	
	15. Head necking		0.592	
	16. Drinking/eating		0.582	

Table4. Fit indices for CFA

Index	χ^2	df	χ^2/df	P-value	CFI	RMSEA	SRMR
Value	3.13	1.04	0.254	0.254	1.00	0.008	0.011

Moreover, results of fit indices, containing goodness-of-fit index (GFI), adjusted of goodness-of-fit index (AGFI), Normed fit index (NFI), comparative fit index (CFI) along with RMSEA and SRMR are reported in table 5 which confirm an acceptable fit of the model.

Table 5. Goodness-of fit indices for SEM

GFI	NFI	RMSEA	CFI	SRMR
0.97	0.93	0.021	0.99	0.024

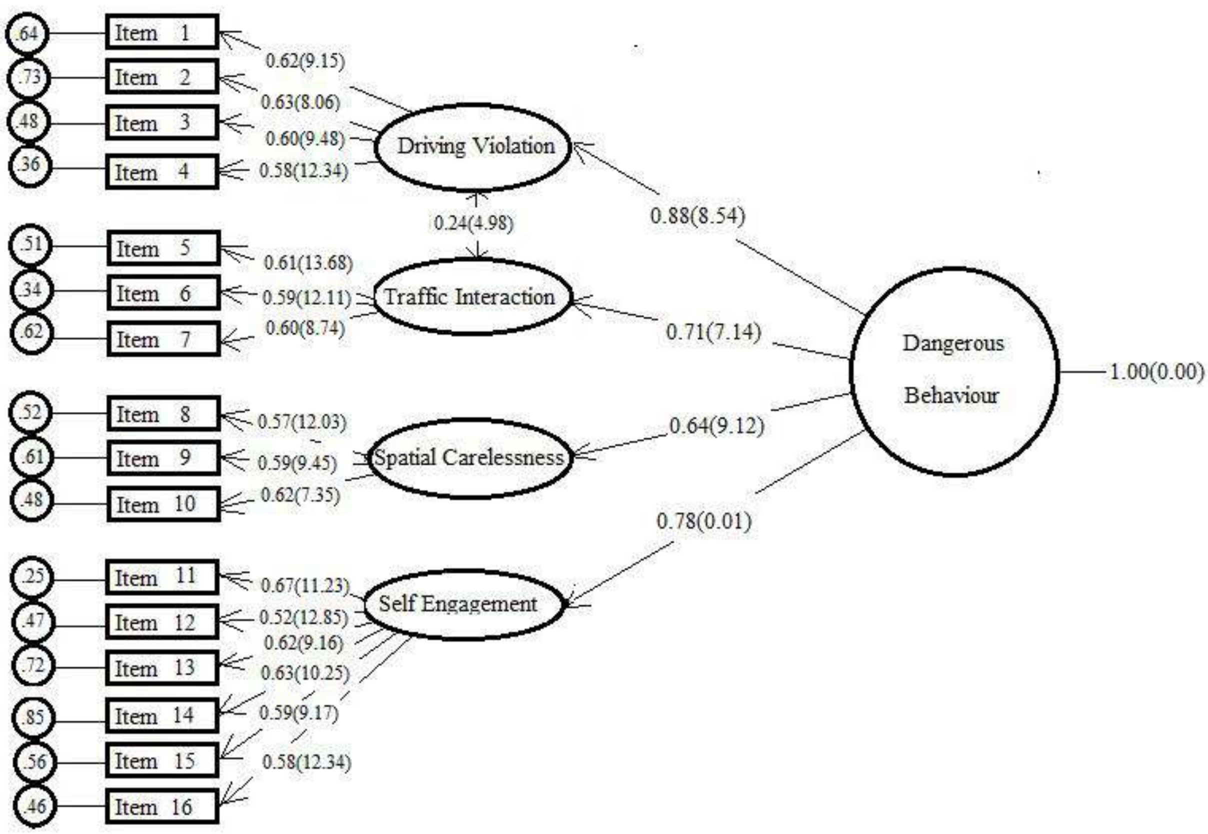

Figure 2. Confirmatory Factor Analysis for the latent variable: Dangerous Behavior

4. Discussion

The aims of present study were:

1. To validate a questionnaire for a self-report dangerous behavior of professional (passenger/freight) vehicle drivers of intercity road network.
2. To measure the latent variable of “dangerous behavior” from provided instrument which depicts the main factors that construct dangerous driving behavior.
3. To explore the association of dangerous behavior on accident
4. To explore the mediating role of penalties on accident to support the reducing role of supervising drivers on number of road accidents.

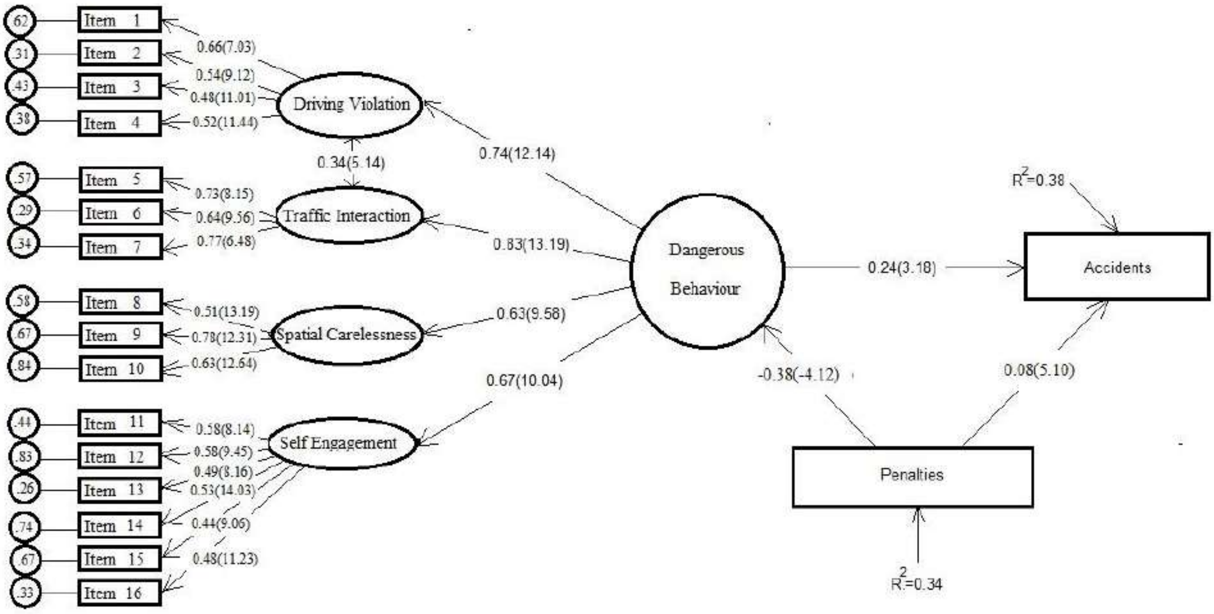

Figure 3. Structural equation model of study

χsquare=70.64; df=74; p=0.5714; RMSEA=0.000

Dangerous behavior of drivers is regarded as a strong cause of road traffic fatalities and injuries (Dotse and Rowe, 2021, Ge et. al., 2023). However, determining dangerous behavior as a latent variable would not be possible through a direct measurement. While different technological instruments are provided, in vehicle or on road, they are not yet able to cover all behaviors of drivers. For example, public vehicles (bus, passenger cars and trucks) are equipped to black box in Iran. Speed cameras are also provided approximately every 2.5 kilometers of each highway and main road. These kinds of equipment provide worthy data especially about speed, however driver's dangerous behavior such as sudden lane change or not observing right of way of other vehicles cannot be determined; hence self-reported questionnaires are practical ways for researchers to assess the behavior of the drivers (hill et. al., 2023). This research has successfully validated a questionnaire which can be used among professional drivers for intercity transport in Iran. Results indicates that four main factors construct the dangerous behavior of professional drivers. The first and second factors with the highest explained variance consist of those behaviors which usually effects on the severity of the potential collision. Exceed speed limit, the strongest item is well known as main contributor to accident. More severity is experienced duo to higher energy release and hence more fatalities (Siskind et al., 2011; Donaldson et al., 2006), vulnerability of pedestrians (Hussain et al., 2019) and less time to react properly (William et al, 2006; Aarts & Van Schagen 2006). Moreover, crossing solid line, especially on two-way roads increases the risk of face-to-face collision, which similar to high speed, can lead to severe collision and high rate of fatality. Sudden brake and stop/park in inappropriate location are other measures of first factor. Hard braking was previously determined as an accident leading factor as well. For instance, according to Desai et. al. (2020) there were approximately 1 crash per mile for every 147 hard-brake in summer 2019 in India.

While measures of the first factor generally relate to a driver independent behavior, second factor consists of measures in which a driver shows a dangerous behavior while interacting with other vehicles. Overtaking, not observing right-of-way and blocking speed way are the three measures of this factor. It seems that such behaviors annoy other drivers and may motivate them to show an unsafe behavior in return. For example, trucks and buses are not expected to block speed way. If drivers of such large size vehicles do not allow other drivers to overtake, they may be incensed to overtake from right hand side. Worth to mention that most calls to 141 is related to those behaviors of professional drivers that had annoyed other drivers. Measures of the second factor include those behaviors that may lead to an accident in which the main culprit (the violator professional driver) may not necessarily involves. Worth to mention that a significant correlation was explored between the first and the second factor which seems logic. For example, a driver may exceed speed limit and at the same time block the speed way.

Third factor contains measures that represent carelessness of drivers to keep the vehicle in a single lane or in a safe distance from other vehicles. Such situation may again lead other drivers (especially unexperienced ones) to fail safe driving.

Finally, the last factor consists of measures that reflect those behaviors that disturb sight, hearing and overall attention of the drivers. Similar behaviors were previously mentioned by other researchers as well (De Winter & Dodou, 2010, 2016; Mokarami et al., 2019). Although these behaviors are categorized as dangerous behavior which can increase the risk of collision, they can be restricted by co-drivers. Co-drivers for bus and trucks are mandatory in Iran, however, the driving task is mostly performed by the main driver in practice. Herein image processing of in-vehicle camera can be used as a supervising instrument. Sharing driving task with co-driver offers enough time for eating, drinking, using phone cell, corresponding to passengers and even sleeping. Obviously, this solution cannot be applied in passenger cars where only a single driver is responsible.

CFA presented acceptable exploratory correlation between factors and the latent variable, confirming with the result of the t-test. Thus, overall good validity and fitness was obtained for the structure.

Worth to mention that while the initial measures were provided of which 16 final items were extracted, drivers were the ones who committed such behaviors. They, as professional drivers, assess self-behaviors as dangerous. Therefore, the initial step to persuade them for behavioral change had been previously taken, and that is adequate consciousness for behavioral change necessity. Herein providing information about the effect of their behavior on fatalities and injuries along with adequate training, effective fining and appropriate supervising would be useful solutions to persuade drivers for safe driving.

Further this research has explored the effect of dangerous behavior of drivers on accidents they had previously experienced. Acceptable goodness-of-fit of indices confirmed the capability of the structure to present causal relationship of the latent variable with accidents. Moreover, this study found evidence about the mediation role of the penalties. As clarifies by the structure, more dangerous behavior leads to more accidents. More penalties also increase accident. This shows that more risk-taking drivers, which got more penalties, were more involved in accidents, however penalties in return by limiting dangerous behavior finally mediates its effect on accident frequency. In another word, dangerous behavior of drivers, if not totally, at least partially avoid dangerous behaviour and in the absence of these penalties more accidents were expected due to dangerous behaviour of professional drivers.

Furthermore, comparing the load factors suggests:

1- Obviously, all dangerous behaviors do not necessarily result in a collision, hence the rate of getting penalties is higher than occurrence of a crash. Two reasons can be discussed in here. First; there are several sorts of observing a driver: Public, police and RMTO. This increase the probability of being blamed by a single, even a slight, dangerous behavior. Occurrence of a crash on the other hand, is generally the result of a chain of causes. Second; all penalties are not necessarily realistic because they are based on judgment of public, expert of RMTO or police officers. However, number of accidents is a simple count of deterministic situations.

2- Number of penalties showed an increasing direct effect on accidents. This suggest that risk taking drivers involve more in accidents. Albeit, risk taking behaviour could not be measured by just one item “number of penalties”, however more risky behaviour increases the probability of being penalized. However negative significant relation of penalties on dangerous behaviour, while mediating the effect on accident, remains a total negative effect of penalties on accident frequency. This result confirms that more penalties will limit drivers in dangerous behaving and successfully decrease accident frequency.

3- While penalties have a decreasing effect by mediating the relationship of dangerous behavior on accidents, the load factor is very small in comparison effect of the dangerous behaviour. From one point of view, this means that penalties are not adequate and thus not capable enough to prevent accidents. This calls for a stricter supervision on professional drivers. This could be in the form of discover more violation or in the form of reacting them. Violation may be explored but disregarded by police officers and RMTO. From another point of view a comprehensive plan, rather than penalties, is required for behavioral change. Cooper (1997) mentioned previously that drivers with more tickets were more likely to be involved in future accidents. Such results reflect the failure of penalties such as fine tickets, as the unique tool, and represent the necessity of novel solution in which other preventing/persuading strategies are applied. For example, motivation the sense of responsibility of drivers could be an effective way. The reason is that, it may be impossible to supervise all behaviors of drivers in all locations and all times due to many technological and economical limitations, and all of them are not categorized as “violation”. Hence self-control is required to protect drivers’ behavior in a safe and defense driving frame.

Furthermore, as the validated instrument is a self-reported scale, it is highly dependent on the self judgement of the respondent on behaving and driving experience. Therefore, focusing on professional drivers which provide a rather homogenous community could be regarded as the strength of this study. This, at the same time explains that why a new instrument was required although several previous instruments had been provided. Nevertheless, because initial items and further choosing among them and next validating the instrument were totally conducted by professional drivers and related experts, the final instrument best suits for such drivers. A same justification could be discussed for the type of the network under study. Driving characteristics in urban network differs from intercity networks and so do the dangerous behaviors and violations. For example, crossing red light, stopping out of bus stop are of meaningful violations in urban network which are not included in the questionnaire. Hence the instrument well suits for intercity networks.

5. Conclusion

This study has presented a reliable and valid instrument that measures the behavior of professional drivers as a latent behavior. While different instruments have been validated previously by other researches, to our best knowledge, it is the first time that the behavior

of professional drivers (passenger car, bus, truck) in intercity network has been focused.
Further modelling process of this research has indicated the role of dangerous behavior on accident. Moreover, the mediating role of penalties on the relationship between dangerous behavior and accidents was indicated. Public reports which lead to RMTO action as well as official police tickets has been recognized as effective tool for supervising professional drivers. Results showed that supervising drivers can significantly reduce rate of accidents, however present penalties are not adequate. In addition to increase strict supervision, novel strategies are required to motivate drivers for behavioral changes such as providing adequate information about the effect of dangerous driving on the total fatalities, injuries and financial losses. Additionally, number of penalties was considered in this study. a more realistic sight could be obtained by considering number of penalties. This can better reveal that more violation is needed to be discovered or a heavier penalty is required to be applied for a better result. Next study would focus on this issue.
The result of this study may be of concern of policy makers for safe transportation on intercity road network and mainly for RMTO in Iran through organizational role on intercity Iranian professional drivers.

6. Acknowledgement

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Research Paper

Analysis and Evaluation of the Technical and Economic Application of RFID, GPS and GIS in Road Transportation

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Abstract

Today, with the growing population and increasing demand for the use of private cars, managing the demand without the use of smart electronic devices, will be complicated and somewhat impossible. One of the methods of demand management is the use of intelligent traffic control systems and pricing accordingly. In this research, in addition to investigating the use of intelligent radio frequency identification systems (RFID), geographic information systems (GIS), and global positioning systems (GPS) in road transportation, a model has been presented to obtain appropriate values. The toll rate and pricing based on the car's useful presence time in the high-traffic area are introduced using smart systems and the use of the Laspeyres index economic relation is presented as an innovation in this research. From the results of this research, we can mention the reduction of vehicle density in the region, improvement of vehicle control in the city, and encouraging people to use the public transportation system.

Keywords: road transportation; crowdedness Pricing; Radio Identification System (RFID); Global Positioning System (GPS); Geographic Information System (GIS); Demand Management

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1. Introduction

Today more than at any time in history, the term time is used in human's daily dialogue. This is due to the fact that it is now established in everyone's belief that the progress and development of countries have been due to the time-saving policies that their authorities or individuals had conducted. It is well known that in the past 400 hundred years, countries with more canals and inland waterways experienced dramatic progress in various aspects which is mainly due to cost efficiency in their transportation in addition to saving time and effort. However, regarding the present time, due to the progress in automobile engineering [Chandran, and Joshi, 2016, Ahmadian, 2017] and hence the highways and bridges [Li et al.2014], in addition to waterways [Charles, 1965], a new concern has emerged regarding transport and commutation. The problem that every community is facing in this regard is due to the population increase [Olstrup et al.2018]. An increase in the population is directly proportional to road traffic congestion which would result in harmful environmental pollution [ko, Myung, 2019], in addition to social [Oguchi et al.2011] and economic costs [Bin hu et al.2009].

The recent progress in intelligent systems has paved the way for enabling coordination in addition to controlling issues regarding traffic congestion. Now since the attitude of a driver is affected by various external players namely the physical conditions of the street and the weather conditions together with the traffic rules, a simulation in this context has been named the "intelligent drivers model" [Treiber et al.2000]. In the present study, an intelligent system has been proposed in the context of transport regarding controllers and coordinators that improve issues in the context of road congestion. The aim is to provide a model to reduce the economic and social marginal costs by encouraging people to use public transportation in order to experience an emergence of a new culture in public transport in the community.

In the current research, the aim is to explain the role of different actors in improving traffic congestion due to the use of intelligent systems. In this way, a pricing model has been proposed to reduce congestion, which is based on the cooperation of introduced intelligent systems. The radio frequency identification system provides a suitable platform for object identification, data collection, and object management. The Global Positioning Satellite System is also a positioning system that uses several satellites that, by implementing the triangulation method, determine the exact location of the person to whom the mobile receiver is connected. The GIS provides access to all information by storing geographic information. Therefore, any changes, modifications, and actions of other operators can be considered. Before proceeding, it is worth explaining the theory of electromagnetic waves. In 1846, Faraday discovered that light and radio waves were part of the electromagnetic energy spectrum, paving the way for Maxwell to present his theory of electromagnetic waves in 1864. However, it was not until 1896 that Marconi succeeded in sending and receiving radio waves in both directions. The Atlantic In 1944, equipped a combat aircraft with a radio identification system as large as a luggage bag to detect enemy planes. In 1948, Henry Stockman raised the idea of introducing a radio identification system in communication, which was termed "communication by radiant power". This led to further advancements in the use of radio waves, which implemented a one-way transmitter and receiver to control the origin of goods. In the 1980s, the radio identification system was used to control the movement of vehicles and the movement of company employees in Norway. A radio identification system was used within ID cards in 2003 before enabling identifying people by chip injections under the human skin 2005, see ref [24] and references therein. In 2006, the books of the Central Library of Munich (Germany) were equipped with the label of the radio identification system, and the "Smart Library" was exploited. Yang and Huang (2005) presented various methods for obtaining the amount of toll together with the position of the ring roads [Yang, huang, 2005]. Zhou Yang and Mark L.Franz (2018) analyzed Washington DC taxi demand using Gps and land-use data which showed a strong link between the demand for taxis, land-use patterns, and accessibility to other modes. They also found that the taxi mode of travel is likely to complement subway trips but compete with bus trips [Yang et al.2018]. Philip T. Blythe (2000) provided insight into the use of in-vehicle tags and transmitters to facilitate road travel. Vehicle data communication for electronic pricing systems and road usage, as well as pricing of trucks by the amount of load, moved have been modeled [Blythe, 2000]. In another research, Sadeghian et al. reviewed methods in transport mode detection based on GPS tracking data [Sadeghian et al.2021]. Also, Subramanya et al. evaluated E-Ticketing Technology in the Construction of Highway Projects [Subramanya et al.2022].

Currently, the aim is to provide a method that, in addition to considering the opinion of experts in transportation matters, uses the influential factors in crowded areas to measure the importance of each factor. The amount of casualties is obtained by going through a correlation theory based on previous studies and using the Laspeyres index method [Laspeyres, 1890] according to the distance traveled and the duration of being in the area. In past studies, instead of other control tools, to predict traffic jams and receive tolls, traditional and annual methods were used. Therefore, it is problematic to update the system according to the passed variables. Collecting tolls traditionally and semi-electronically in different ways, including field observations and traffic counting, which is a very costly and time-consuming solution, and the more important problem is that there is no focus on the presence of vehicles in the crowded area. In this research, the tolls received from passing vehicles are more accurately compared to the traditional methods in shorter periods by using modern equipment and calculating the number of tolls and it is received as a variable for different periods of the year.

2. Materials and Methods

The first step in determining a suitable system for pricing is determining the effective factors in the region, which should be identified and evaluated by experts and researchers. In this study, based on the summary of similar records and expert opinions, the following factors are included in the proposed model. Additionally, considering the characteristics of the target area, the basic information of the desired range is extracted from organizations and statistical websites and incorporated into the proposed model. This model uses a non-linear programming pricing model [Blythe, 2000] instead of using the usual two-level model [Bazaraa et al.2010] to determine the amount of charges. bilevel (two-level) linear programming (blp) is an optimization problem in which the decision changes in the optimal set become a second-level optimization problem and has continuous changes and linear objective functions. In general, it can be said that in one-level planning, there is a decision maker and he decides on all the variables and all the resources are at his disposal. For this reason, this type of planning is called centralized planning. But, two-level planning is a useful tool for modeling decentralized decision-making. This model reduces the problems of finding the amount of complications [Verhoef, 2000 and, Hern and Ramana, 1998].

The methodology is as follows:

after selecting the influential factors based on the specified range and considering the pricing model and expert opinions, the weight of each factor is determined. Finally, using a hierarchical method, the importance percentage of each mentioned factor is obtained.

3. Case Study

A case study was conducted in District 11 of Tehran Municipality, the capital city of Iran. The study area covers the southern part of Valiasr Street, from Rah Ahan Square to Theatre Shahr Intersection. The reason for selecting this area is its high traffic flow as it is one of the busiest areas in Tehran. All traffic control plans and transportation modes, including high-speed bus lines and subway lines, are implemented in this area, making it a significant area in the city. The study area is depicted in Figure 1.

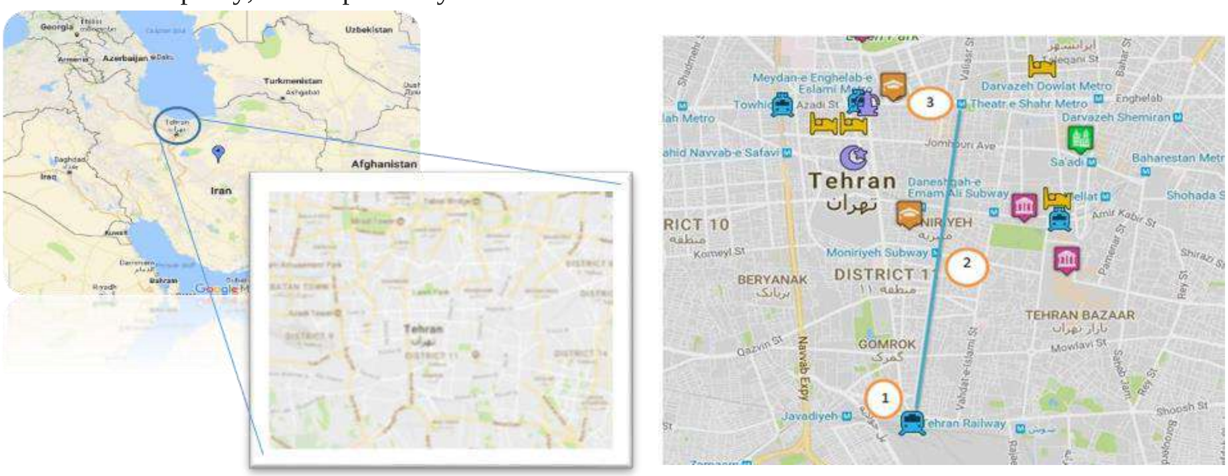

Figure 1. Scope and zoning

In this research, the study area is divided into three zones based on land use. Each land use category contributes to the traffic factors within the specified area, and pricing can be determined accordingly. The mentioned area encompasses all land uses except industrial. The area is divided into the following three zones:

Zone 1: Between the origin (Rah Ahan Square) and the destination (Muniriyeh Square), predominantly residential land use.

Zone 2: Between Moniriyeh Square to the intersection of Jomhuri Street. The dominant land use in this zone is commercial.

Zone 3: From the Jomhuri intersection to the Theatre Shahr intersection, including the intersection of Enqelab Street and Valiasr Street. The dominant land use in this zone is commercial and administrative.

After the zoning based on land use, the distance of each zone is determined using local surveys and Google Maps. Also, the distance traveled by each vehicle can be measured using smart

electronic devices to assess the duration of presence and congestion in the designated area. Finally, after determining the distance of each zone, it is necessary to calculate the duration of vehicle presence in each zone. This information can be obtained from the intelligent systems introduced in this study. Moreover, the level of useful presence time in each zone will be determined according to expert opinions and incorporated into the pricing model.

The travel time is calculated based on the design speed limit of the studied area and the length of the route without considering the stop times. Information regarding travel attractions, car ownership, and population in the studied area was obtained through the Tehran Atlas and consulting the relevant municipality. It should be noted that the accessible information on the mentioned website has a one-year delay. The data used in this study corresponds to the years 1393-1394. The information is presented in Tables 1 to 4. By using the acquired information and the weight coefficient of each factor, it is possible to prioritize the factors related to congestion in different regions.

Table 1. Regional Population Specifications

Population (people)	area
110032	First area
75365	Second area
110781	Third area
296178	Total

Table 2. Travel Attraction Level of the Studied Regions

Travel attraction	area
1200	First area
1000	Second area
1700	Third area
3900	Total

Table 3. Ownership and number of vehicles by Region

Car (number)	area
38511	First area
18841	Second area
44312	Third area
101664	Total

Table 4. The travel time between Regions at 40 km/h

Travel time (s)	area
425	First area
276	Second area
423	Third area
1125	Total

The factors directly affecting traffic congestion in the designated area, according to transportation experts and previous studies, can be classified as follows:

- Travel attraction level by region
- Number of vehicles in each region based on resident households in the area
- Population of each region
- Travel time between each region

Note: Volume-to-capacity ratio (if less than zero, the area is not congested and is not included in the calculations)

Based on the defined factors and the obtained coefficients for each factor, a simple linear mathematical relationship between the factors can be derived using the hierarchical method. The relationships for each index are as follows:

A) Burden indicator for each area

$$Pz = \sum_{1}^{n} \alpha_{S_i} * S_i \quad (1)$$

Using Eq. (1), the values of each factor specified in Table 2 are multiplied by the assigned importance coefficients, resulting in the congestion index for each region.

The Variables are defined as follows:

S_1: Travel attraction level by region

S_2: Number of vehicles in each region based on resident households in the area

S_3: population of each region

S_4: Travel time between each region

α_{si}: Coefficients and weights of the influencing factors in the pricing model

S_i: Percentage of the importance of extracted factors

B) The amount of basic toll

The amount of toll in crowded areas should be determined according to studies and the needs of the area. In this study, since the magnitude of the toll for each area is not specified, the base price is selected based on the most cost-effective mode of transport on the studied route.

C) Reference Price Index Ratio

According to equation (1) and considering the volume-to-capacity ratio, the region with a value closer to one has a higher congestion level and volume. To determine this congestion level, the reference price index ratio is calculated by dividing the price index of the origin region by the price index of the destination region. It should be noted that the region with a lower price index is considered as the origin in the equation.

$$k_{od} = \frac{k_{po}}{k_{pd}} \quad (2)$$

Where the variables are described as follows:

k_{po}: Price index of the origin or base area (minimum value)

k_{pd}: Price index of the destination area

Finally, the maximum obtained value close to one is considered as the reference price index.

D) The price index of each area

Using equation 2, known as the Laspeyres equation, after determining the reference price index for the base area, to obtain the price index of each other area, first calculate the ratio of their indices similar to equation (3). Divide the obtained value by the reference price index ratio and multiply it by the assumed base price between the areas. The entry price between those two areas is calculated.

$$\beta_{od} = \frac{k_{od}}{k_{ods}} \times \beta \quad (3)$$

In this equation, the variables are described as follows:

k_{od}: The price index of each area based on equation (2)

k_{ods}: Base price index

β: Assumed base price

Now, if there is a route passing through different areas, the sum of the price indices of each area is calculated according to equation (4).

$$\beta_{od} = \sum_{i=1}^{n} \beta_{odi} \quad (4)$$

Despite the radio identification system, the global positioning system, and the geographic information system that record the distance and entry time into the area, it is sufficient to calculate the congestion price based on equation 5 for the busiest route in terms of distance between the origin and the congested area and the price per traversal is obtained based on the congestion area.

$$\beta_{odu} = \frac{\beta_{od}}{x(m)} \quad (5)$$

4. Results

After determining the assigned weight coefficients and their importance using the hierarchical method, the importance degree of each factor will be obtained as described in Table 5.

Table 5. The coefficients of the factors and the defined weights based on their importance in the relevant area

	Car ownership	Trip time	Population	Travel attraction
coefficients of the factors	25%	15%	25%	35%
The degree of importance	2	3	2	1

Table 6. Price Index of Regions

area	Price Index
First area	37622
Second area	23944
Third area	39411

4.1. The Basis of the Congestion of Each Area

Using Eq. (1), the values for each of the factors introduced by the tables multiplied by the assigned importance coefficient the price index of each area is determined.

It should be noted that a region with a lower price index is selected as the origin. By using the obtained information, the price index for each area is calculated according to Table 6.

These numbers indicate the level of traffic and congestion in each area based on the factors influencing the research in that region. Accordingly, entering a busier area will require paying higher fees.

According to equation (1) and considering the volume-to-capacity ratio of each area, the area with a value closer to one for the price indices between the two areas is considered the more congested area. To determine the level of congestion, the price index of the origin area is divided by the price index of the destination area in each region, and the ratio of the reference price index for the most congested and critical path is determined. It should be noted that the area with a lower price index should be considered as the origin in the equation.

Finally, the highest obtained value close to one is considered as the reference price index.

Table 7. The price indices between the areas

Price index	Area
0.64	1st and 2nd area
0.61	2nd and 3rd area
0.95	1st and 3rd areas

As observed, the first and third areas have the highest values, which can be considered as congested areas for pricing purposes. Thus, Area 1 is the numerator and Area 3 is the denominator, and the reference price index is obtained for the two congested areas.

To price the plan as the baseline cost of the proposed pattern, the cost of using a taxi as the most expensive and congested mode of transportation for the most congested path is considered, with a base fare of 10,000 Tomans as the revenue from the path, and the baseline cost (β) is taken into account.

In equation (3), the ratio of the price index of the desired path is calculated according to equation (2), and the result is divided by the ratio of the price index of the most congested path (Area 1 and 3), and the obtained number is multiplied by the revenue base cost. The resulting revenue is calculated and presented in Table 8.

Table 8. Tolls from the busy model introduced

Route tolls β_{odu} (Toman)	Baseline toll B (Toman)	The ratio of price indexes β_{od}	Base price index ratio (K_{ods})	Passing areas	Route number
10000	10000	0.95	0.95	1-3	1
6667		0.633		1-2	2
6364		0.604		2-3	3

As observed, higher revenues are collected for entering areas with higher travel attractions. Furthermore, the distances of the paths using private vehicles and satellite imagery are shown in Table 8. The highest cost obtained from the revenues, as shown in Table 7, is calculated based on the distance of the path, and the prices are listed according to the distance in the table. The other paths are calculated based on their respective distances and the price based on the distance of the most congested path.

Table 9. Routes Distance

Distance (m)	Area
4926	1st to 2nd areas
3170	2nd and 3rd areas
8096	1st and 3rd areas

Table 10. Prices in terms of the route length

Cost of mileage (Toman)	area
0.75	First area
0.48	second area
1.24	Third area

According to equation (4), first, the revenue collected from the most congested path, i.e., Path 1 to 3 (βodu), is divided by the distance between these two areas according to Table 9. It is considered as the baseline price based on the traveled distance, and the remaining areas are calculated relative to the specified revenue base cost and listed in Table 10.

The obtained fees for each area are calculated based on the travel time between the origin and destination of that area without considering the additional delay time on the route, which is provided in Table 13. For each additional presence, including the distance traveled and the additional time spent in the area, higher fees are charged relative to the specified amounts.

5. Discussion and Conclusion

In this study, the formula for determining price indices and prices based on distance and presence time in the desired area was determined using the economic price indices of Laspeyres and the variables and constraints of previous pricing models. Intelligent devices were introduced in this research, which can record the duration of a vehicle's presence in the area and the distance traveled on the route. Based on the basic information of that area, they calculate the pricing based on the congestion level of the area. In fact, to calculate how much this vehicle contributes to the congestion of the area, radio identification systems, along with code readers, register the entry and exit of the vehicle at the entry and exit points of each area. The required time for passing through the areas, including travel time based on the planned speed on the route and time wasted due to vehicle stops on the route, traffic lights, tolls on the route, etc., are included in the allowable route times. Times exceeding the defined times are considered as receiving additional fees compared to the defined fees. If a vehicle has a longer presence time in the area, calculated without stopping time plus authorized stops such as traffic lights and speed breakers, it will incur higher fees.

For comparison and based on the obtained distances and prices in Tables 9 and 10 for a trip from the first area to the third area, as well as the cost of public transportation according to Table 11 and equation (6), the cost of the trip with private vehicles to different transportation modes will be determined.

$$A = \frac{P * X}{G} \tag{6}$$

P = determined cost according to third region scrolling based on table 10 (1.24)
X = the third region scrolling (8096 meters)
G = transportation cost at the third region according to Table 11.

Table 11. Travel costs

The proportion of travel expenses by personal means to public transport	Passenger Passage Traffic Vehicle in the Third Occupied Area (Toman) (G)	The Device
20	500	BRT
14	700	SUBWAY
4	2500	TAXI

Based on the updated costs (table 11), considering the route distance, traveling by private vehicle is respectively 20, 14, and 4 times more expensive rather than the BRT, Subway, and Taxi transportation modes.

A result of this research is decreasing the region's crowded by up to 50%, the crowding of the region is due to stopped cars for long times. Made studies of the region indicate that most trips were done by private vehicle for commercial purposes and it can be done by other transportation modes.

By the implementation of this study, reducing congestion, improving vehicle control within the city limits, encouraging people to use public transportation system instead of private vehicles, decreasing air pollution, updating the urban traffic control, increasing the government income, more efficiency and less fuel consumption, controlling the passing cars about insurance coverage and technical examination and the implement of low emission zone (Green Zone based on vehicles pollution) will be obtained.

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Research Paper

A Joint Mode Change and Mode Choice Decision under Transportation Demand Management Policies (Case of a Copula Approach)

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Abstract
As policymakers suggest using Transportation Demand Management (TDM) strategies, understanding the roots of the differences between the predicted and actual results of these policies' implementation is an area of interest for research. Among diverse reasons studies identify for this gap, this study focuses on model capabilities, using copula-based joint models for modal shift and mode choice. The study offered a hypothetical bundle of TDM strategies to 577 commuters who regularly drove to their workplaces during peak hours. Their stated mode choices were gathered. Thereupon, two successive steps were captured from their decision-making process: first, the decision to give up driving or not, and second, the substitute chosen mode if leaving driving was adopted. The joint effect of changing/not changing the travel mode from a private car and picking an alternative while facing a package of TDM strategies was tested with the copula approach. A binary logit is used to model the mode change decision, and the mode choice is modelled using a multinomial logit. Finally, among several copula functions, Frank Copula with the highest maximum likelihood estimation, and the positive value of dependency parameter, with an adjusted ρ2 of 0.158 was chosen as the best model. The findings of this study highlight the importance of considering people's previous mode decisions while trying to increase transit and decrease private use with TDM policies, which was not addressed in the literature using a dependent joint structure.

Keywords: copula-based models, transportation demand management, mode choice, modal shift

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1. Introduction

Transportation is one of the high-rate non-renewable energy consumer sectors. It also pollutes the environment. So, policymakers tried to participate in the transition to sustainable transportation in recent years. Transportation demand management (TDM) as a low-cost solution compared to heavy investments for new transportation facilities has its supporters. As TDM policies mostly try to use the existing infrastructures efficiently and to make the road network less congested as well, the bad impacts of the sector will be lessened.

Many of the TDM strategies aim to change the trip mode from private cars. Therefore, regular commute drivers are the main target of TDM policies. Many studies focus on modeling the mode choice after facing one or a bundle of TDM strategies based on revealed and stated preference data. For instance, Washbrook used a set of stated preference data to test the effects of different levels of road pricing and parking charges, besides the diverse rank of travel time for distinct alternative modes on the demand for single-occupant vehicles [Washbrook, 2006]. Anwar and Yang considering the poor access to public transportation as a major cause of private vehicle tendency, introduced two public transport policies: (i) once-an-hour direct bus services from home to university, and (ii) park-and-ride facilities [Anwar and Yang; 2017]. In a more recent study, Anwar and his colleagues investigated the modal shift to the metro from cars in Saudi Arabia [Anwar et al., 2023]. These articles try to recognize the decision-making processes and the main factors affecting the mode choice decision and to help the policymakers estimate the results of implementing these policies in advance. However, there is still a gap between the expected effects of these practices and the real results. The difference could originate in diverse bases such as researchers' inaccurate understanding of individuals' decision-making processes in dealing with these policies.

Many studies modeling mode choice in response to TDM policies use a discrete choice model as if respondents feel neutral about the choices at first. However, giving up driving and choosing a new mode in response to TDM policies seems to be a two-decision-making process rather than just a mode choice decision. In other words, giving up driving and adopting a new mode to use, looks to be two simultaneous choices. The current study tries to test this idea and examines the joint structure between these two decisions. Finding an approvable joint structure with effective variables suggests that change mode and mode choice should be considered differently. In other words, while planning to use TDM strategies, planners should know which policy will affect current regular users of each trip mode and which will influence new or infrequent users' choices.

Among different approaches to applying joint models, as a first try nested logit was tested according to its excessive and usual use. Results revealed that nested logit is not an acceptable structure for the joint model of change mode and choose a new one. Seemingly the hierarchy of the two choices is different from the one captured in regular nested logit structure. So, a Copula-based structure is chosen for its flexibility in assumptions. A basic assumption in this framework is that the two decisions share common observed and unobserved factors [Train, 1986]. A copula-based joint binary logit-multinomial logit (BL-MNL) modeling framework is developed. Although, several researchers have focused on different copula-based structures in different areas of studies [for example, Bhat and Eluru, 2009; Portoghese, et al., 2011; Pourabdollahi, et al., 2013; Li et al., 2023; Wali et al., 2023], to the authors' knowledge this study is the first use of copula-based joint modeling for the simultaneous decision-making issue of changing current mode and choosing a new one.

The paper continues with a review of related literature, followed by an introduction of the data. Then in the methodology of the copula joint model approach, the choices and descriptive variables are discussed. Afterward, the paper demonstrates the final model and concludes with a discussion of the results and some suggestions for future research.

2. Literature Review

Focusing on TDM as a low-cost answer to the congestion problem, several studies have tried to find the effectiveness of different TDM strategies individually or in bundles. Many of these studies use discrete choice models to model the 'mode choice decision' in the presence of demand management policies [Washbrook, 2006; Shahangian et al., 2012; Kavta and Goswami, 2022; Wang et al., 2022]. Some few ones concentrate on individuals who have a regular plan for their trips and while facing a set of TDM policies, they need to consider changing their routine and making a new one. In other words, some believe that it is not a mode choice but first, a mode change decision to make. Satiennam et al. used a set of stated preference data to investigate the potential modal shift of car and motorcycle users to bus rapid transit (BRT). They used two separate binary logit models for regular car users and motorcycle riders. The paper concluded that the presence of the BRT can significantly attract both the private car and the motorcycle users to shift to BRT. However, the shift proportion of motorcycle users was higher than that of car users. Moreover, the final model reveals that some socio-economic factors such as gender, age, having a driving license, and residential location are effective in choosing the BRT [Satiennam et al., 2016]. In another study, Erikson et al. revealed that a combination of two push and pull policies (raised tax on fossil fuel, and improved public transport) led to a larger reduction in the usage of private cars compared to when the measures (i.e., raised tax or improved transit) evaluated individually. They also concluded that the reduction was mainly expected to be made through trip chaining and changing the travel mode. They also tested some psychological factors in two groups: 'intention to reduce car use', and 'personal norm to reduce car use'. These factors appeared to be more effective than gender, age, income, and car access [Erikson et al., 2010]. Kwan et al. examined the binary logistic regression to figure out the relation between the trip characteristics and the intention to shift from private motor vehicles to rail transport. Conclusions illustrated that factors such as trip duration, distance, purpose, vehicle occupancy, and presence of child passengers were considerably associated with the intention to shift [Kwan et al., 2018]. More recently, Chiu explored mass rapid transit effects on motorcycle use. Findings show that both newly introduced metro stations and older existing ones, affect motorcycle share and households' vehicle kilometers traveled [Chiu, 2023]

Li et al., providing a stage-based framework, tried to show the mode shift decision-making process (whether users will shift from private cars to public transit, biking, or walking or continue using cars) under the implementation of some strategies. They used stated preference data to observe the impacts of congestion pricing and some reward strategies on morning commute drives. Results revealed that the former strategy is more important than the latter [Li et al., 2019]. In another study of the combination of both psychological and policy factors, Dirgahayani and Sutanto combined the theory of planned behavior (TPB) and the policy-specific belief to capture determinants affecting motorized drivers' behavioral inclination to a parking management strategy and the use of a new light rail transit (LRT) system in Bandung City, Indonesia. This study revealed that control beliefs, perceived norms, and acceptance considerably affect people's tendency to use LRT [Dirgahayani and Sutanto, 2020].

Recently, Mashrur et al. studied incentives and operational policies to bring transit ridership back after the COVID-19 pandemic. They used a two-stage model to capture pre- and post-pandemic transit usage of people who did not choose transit during the pandemic. Findings revealed that a package of incentives for transit and increased parking costs may encourage travelers to retake transit [Mashrur et al., 2023]. Sklar’s Theorem explained Copula's function (1959) to express a multivariate distribution in terms of its marginal distributions [Sklar 1973]. The first attempt at copula's study was done by Lee who proposed, a fully joint formulation in which the unobserved error terms were allowed to be non-normal [Lee, 1983]. The usage of the copula approach in the specification of binary models started with Smith who used eight different copulas by normal/normal and normal/gamma marginal distributions [Smith, 2003]. Trivedi and Zimmer used Frank’s copula for negative binomial/normal marginal distributions [Trivedi and Zimmer, 2007] (see also [Nelsen, 2006]). These initial approaches led to the application of copulas in finance, medical science, and transport modeling (starting with [Bhat and Eluru, 2009]).

Afterward, several researchers used copula structures in different areas of transportation studies to describe their statistical models. For example, Portoghese et al. used copula in joint modeling the choice of the work trip mode and the non-work stops during the trip. The mode choice model comprised four choices: drive alone, shared ride, active transport, and public transport. The number of stops included 0, 1, 2, and more than 2 stops [Portoghese et al. 2011]. Frank and Gaussian copulas were implemented to estimate the model. Rasaizadi and Kermanshah also confirmed this hypothetical model's structure in another research [Rasaizadi and Kermanshah, 2018)]. Moreover, Sener and Bhat used copulas to illustrate the dependency between the propensity and the frequency of workers' choice to telecommute. The study reveals that full-time employees have a greater tendency to telecommute than part-time ones. Although, among telecommuters, full-time employees telecommute less than part-time workers. The decision-making process is assumed to be a two-stage one. First, to choose to telecommute or not, then to adopt a telecommuting frequency (once a year, a few times a year, once a month or more, once a week or more, and almost every day). The suggested joint model has a binary/ordered logit framework. Frank copula is selected according to its best fit [Sener and Bhat, 2011]. Ermagun et al. modeled the mode choice and the escort decisions of school trips jointly. Comparing a nested logit and a copula-based model the results reveal that the latter fits the data better [Ermagun et al., 2014]. Ermagun and Samimi examined a copula-based joint discrete/ continuous model to explain the interaction between the mode choice and the travel distance for school trips. In comparison with the conventional estimation, joint formulation estimated higher values for the coefficients of both the travel distance and the travel safety perception [Ermagun and Samimi, 2018]. In another study, Seyedabrishami and Rasa Izadi modeled the mode and departure time choices in urban trips using the copula framework. Testing a binary logit-multinomial logit structure, the estimated copula dependence parameter is approved to be highly significant [Seyedabrishami and Rasa Izadi, 2019]. They also used copula to model the interaction among destination and departure time choices in a later article [Rasa Izadi and Seyedabrishami, 2021]. In another recent study, Jafari Shahdani et al used copula and nested logit to model the interaction between activity choice and duration [Jafari Shahdani et al. 2021]. Pourabdollahi et al. modeled the freight mode and the shipment size choices with a copula-based joint multinomial logit/ multinomial logit [Pourabdollahi et al., 2013]. As another example in the logistics area, Keya et al. tested a copula-based joint model in the form of multinomial logit/ordered logit to model the freight transportation mode and the shipment size as well [Keya et al., 2019]. Bilal et al used a copula-based discrete-count joint model to analyze the decision-making between choice and travel itinerary in intra-destination trips to Jeju Island, South Korea. The results revealed that travelers chose their travel mode first [Bilal et al. 2023].

Although modeling mode choice behavior is common in transportation studies, the authors could not find any study that specifically models the mode choice of current regular commute drivers after facing a bundle of TDM strategies. In other words, a gap was recognized in distinguishing between the decision to choose a travel mode and the two successive decisions of first, to change the current regular transportation mode, and then to adopt a new travel mode, while facing a bunch of pull and push policies. Addressing this gap and applying a copula-based model are among the important contributions of this research.

3. Data

A data set gathered in 2010 in Tehran, is used in this research. Tehran has a restricted CBD, which at the time of data gathering, cars could enter the area either with a yearly prepaid CBD entrance permission every day or according to their plate numbers just in odd or even days. The respondents were regular commuters who drove most of the days, i.e., days that they had permission to enter the zone, to their workplaces/university, located in CBD, during the morning peak period. They were asked to state what mode (among driving, transit, taxi, rideshare, cycle, or other) they would choose in a hypothetical situation of an experiment based on five TDM policy measures. Besides the stated preference part, information on socio-economic characteristics included age, gender, job status, and education of the individual, plus traits like the household's size; the number of cars and motorcycles; the employment status of the family members; also, some data about the regular commute trip attribute such as distance, trip time, the access time to the nearest transit station proper for the commute trip were gathered. Besides, respondents answered a set of questions to reveal the main reasons they regularly prefer to use their private cars rather than other means of transport [Shahangian et al., 2012].

Table 1 shows the key characteristics of the data. As mentioned before, the SP part was designed based on different levels of five policy measures: three aimed to make driving less attractive and two to encourage the use of transit. The driving discouraging policies included a CBD entrance toll (with three levels of $5/day, $10/day, or $15/day), parking charge (of $1.2/day, $2/day, or $3/day), and fuel price ($0.40/L and $0.80/L). The transit access (of the actual access time, or an access time which was 33% lower than the real time) and the transit travel time (expressed relatively to actual time transit with three levels of no change, a 20% decrease, and a 33% decrease) were the two transit encouraging strategies.

The sample used for model estimation includes the answers of 577 respondents, each to six different hypothetical scenarios, which sums up to 3642 observations. In response to the scenarios, each person had 12 different transport mode choices. Finally, according to the small number of respondents choosing some choices, they were combined into six groups of 'private car', 'transit', 'taxi', 'rideshare', 'cycle', and 'walk and other' based on similarities among choices. More details could be found in Shahangian et al. (2012). In 2627 of the situations (75.9%) the respondents decided to change their mode from private cars. Table 2 shows the frequency and the percentage of the adopted choices in these observations.

4. Methodology

This section presents the methodology used in this study, the model derivation, and the structure of the copula-based binary-multinomial logit framework. To model the mode change choice a binary logit and to model the choice of a new travel mode a multinomial logit model is built. Finally, the interrelationship between the two is determined with a copula function.

4.1. Model Structure

The modal shift from a private car is modeled using a binary choice structure. Let q represent individuals. Also, let t_{qk} be the unobserved propensity to shift from the private car or not [Ben-Akiva and Lerman, 1985].

$$t_{qk} = \beta X_{qk} + \varepsilon_{qk} \quad (1)$$

Table 1. Key Characteristics of the Sample

Frequencies			
Characteristic	**Description**	**Absolute Frequency**	**Relative Frequency (percentage)**
Gender	Female	192	33.3
	Male	385	66.7
Age	Less than 30 years	270	46.8
	Between 31 and 50 years	260	45.1
	More than 51 years	47	8.1
Marital Status	Single	236	40.9
	Married	341	59.1
Education	Associate degree or less	145	25.1
	Bachelor’s or master’s degree	355	61.6
	PhD or MD	75	13.0
	No Response	2	0.03
Employment Status	Freelance worker	74	12.8
	Employee	346	59.9
	Student	157	27.2
CBD	House located in CBD	123	21.3
	Otherwise	454	78.7
FGP	Never	226	39.2
	Rarely (less than 25%)	108	18.7
	Sometimes (26% to 50%)	85	14.7
	Usually (more than 50%)	123	21.3
Descriptive Statistics			
Characteristic	Mean	Variance	Range
No. in household	3.50	1.17	1 - 10
No. of driver's licenses in household	2.50	1.08	1 - 6
No. of cars in household	1.56	0.76	1 - 4
Home to work distance (km)	9.19	8.06	0.46 - 62.78

Table 2. Choices' Overview

Alternatives	**Absolute Frequency**	**Relative Frequency (percentage)**
Change mode	2627	75.9
Do not Change mode	835	24.1
Total	3462	100
Transit	1219	46.4
Taxi	1064	40.5
Rideshare	100	3.8
Cycle	71	2.7
Other	173	6.6
Total	2627	100

Where X_{qk} is the column vector of independent variables, β represents a vector of parameters to be estimated and ε_{qk} is the random error term of the utility function. In the usual structure of a binary choice model, the unobserved propensity is reflected in the observed choice [Bhat and Eluru, 2009]. t_{qk}=1 if the qth individual chooses to change mode (choose the choice k) and t_{qk}=0 if the qth individual decides not to change the current private-car mode (choose the choice l). ε_{qk} is assumed to have a Gumbel distribution with a mean of 0 and a variance of 1. The error term captures the effects of unobserved factors in changing mode decisions. So, t_q is also Gumbel-distributed with parameters (βX_q, 1). Person q chooses choice k if its utility is more than the other option.

$$t_{qk} > t_{ql} (l \neq k) \quad (2)$$

If the systematic part of the utility of the choice l is treated to be zero, equation (2) is as:

$$\beta X_{qk} + \varepsilon_{qk} > \varepsilon_{ql}$$
$$\varepsilon_{qk} - \varepsilon_{ql} > -\beta X_{qk} \quad (3)$$

If τ_{qkl} is defined as $\tau_{qkl} = \varepsilon_{qk} - \varepsilon_{ql}$, then:

$$\tau_{qkl} > -\beta X_{qk} \quad (4)$$

So, t_{qk}=1 if and only if $\tau_{qkl} > -\beta X_{qk}$.

As ε_{qk} and ε_{ql} have a Gumble distribution, τ_{qkl} follows a logistic one.

The marginal distribution of τ_{qkl}, i.e., the probability of selecting the choice to change the private car, is shown in equation (5) [Ben-Akiva and Lerman, 1985]:

$$F(-\beta X_{qk}) = \exp(-\beta X_{qk})/(1 + \exp(-\beta X_{qk})) \quad (5)$$

As mentioned before, the multinomial logit formulation was used for the substitute mode selection. Let an individual and a mode successively be indexed with q and i and S_{qi} be the latent utility of person q for adopting the substitute mode i (3):

$$S_{qi} = \gamma_i Z_{qi} + \eta_{qi} \quad (6)$$

Where, Z_{qi} is the observed attribute vector and γ_i is the coefficient vector to be estimated. Moreover, η_{qi} symbolizes the error term which is hypothetically Gumbel-distributed with parameters (0, 1). According to the utility theory, person q chooses i if and only if the condition (7) holds:

$$S_{qi} > \max_{j \neq i} S_{qi} \quad (7)$$

Let S_{qi} be a dummy variable; S_{qi} =1 if the ith substitute mode is chosen by the qth individual, and S_{qi} =0 otherwise. Defining

$$\upsilon_{qi} = \{\max_{j \neq i} S_{qi}\} - \eta_{qi} \quad (8)$$

Using both equations (6) and (7), reveals:

S_{qi} =1 if and only if $\gamma_i Z_{qi} > \upsilon_{qi}$

Equation (8) and the assumption on the η_{qi} gives the intimated marginal distribution of υ_{qi} [Train; 1986]:

$$G(\gamma_i Z_{qi}) = \exp(\gamma_i Z_{qi}) / \textstyle\sum_j \exp(\gamma_i Z_{qj}), j = 1, \ldots, J \quad (9)$$

The joint probability that person q chooses choice k (the giving up driving choice) and a mode i is:

$$\Pr[t_{qk} = 1; s_{qi} = 1] = \Pr[\tau_{qkl} > -\beta X_{qk}; \upsilon_{qi} < \gamma_i Z_{qi}] = \Pr[\upsilon_{qi} < \gamma_i Z_{qi}] - \Pr[\upsilon_{qi} < \gamma_i Z_{qi}; \tau_{qkl} < -\beta X_{qk}] \quad (10)$$

For the calculation of the probability function, a bivariate distribution function between the two error terms is needed. To show the dependency of random variables and make a joint distribution using random variables marginal distribution Copula distribution is useful. [Nelsen, 2006]. We can rewrite equation (10) with copula as:

$$\Pr[t_{qk} = 1; s_{qi} = 1] = G(\gamma_i Z_{qi}) - C_{\theta ki}(G(\gamma_i Z_{qi}); F(-\beta X_{qk})) \quad (11)$$

The marginal distribution functions of change mode and mode choice models are F and G. Moreover, θ_{ik} is the copula dependence parameter and demonstrates the correlation of the utility error terms of the decision to change mode (k) and the new mode (i). Table 3 shows the characteristics of some copulas.

4.2. Estimation Method

Define I[.] as an indicator function equal to 1 if the true condition of the statement in the brackets holds and to 0 if not. And specify:

$$M_{qi} = I[t_q = 1]I[S_{qi} = 1] \quad (12)$$

So, the log-likelihood function has the following form (Sener and Bhat 2011):

$$\text{LogL} = \sum_{q=1}^{Q} I(t_q = 0)\log[\Pr(t_q = 0)] + \sum_{q=1}^{Q}\sum_{i=1}^{I} M_{qi}\text{Log}[\Pr(t_q = 1, S_{qi} = 1)] \quad (13)$$

This means that the log-likelihood function consists of two parts, one relates to respondents who chose not to change their current mode, and the other to the group who first chose to give up driving and then selected their alternate mode. In other words, the former stands for the probability of willing to still use a private car, and the latter for the probability of choosing a new mode after accepting to stop driving.

To estimate the β, the γ, and θ the log-likelihood function should be maximized. R-Studio programming is used for maximizing the log-likelihood as well as to estimate the parameters. Figure 1. Shows the structure of the methodology in a flowchart format.

Table 3. Some Characteristics of Alternative Copula Structures [Smith, 2005]

Copula	C (u_1, u_2)	Dependence parameter range
Frank	$-\theta^{-1}\log\{1+\frac{(e^{-\theta u_1}-1)(e^{-\theta u_2}-1)}{e^{-\theta}-1}\}$	(-∞,∞)
Gumbel	$\exp(-(\tilde{u}_1^{\theta}+\tilde{u}_2^{\theta}))^{1/\theta}$	[1, ∞)
Product	$u_1 u_2$	-
FGM	$u_1 u_2(1+\theta(1-u_1)(1-u_2))$	[-1,1]
AMH	$u_1 u_2(1-\theta(1-u_1)(1-u_2))^{-1}$	[-1,1]
Gaussian	$\Phi_G(\Phi^{-1}(u_1), \Phi^{-1}(u_2); \theta)$	(-1,1)
Clayton	$(u_1^{-\theta}+u_2^{-\theta}-1)^{-1/\theta}$	(0, ∞)

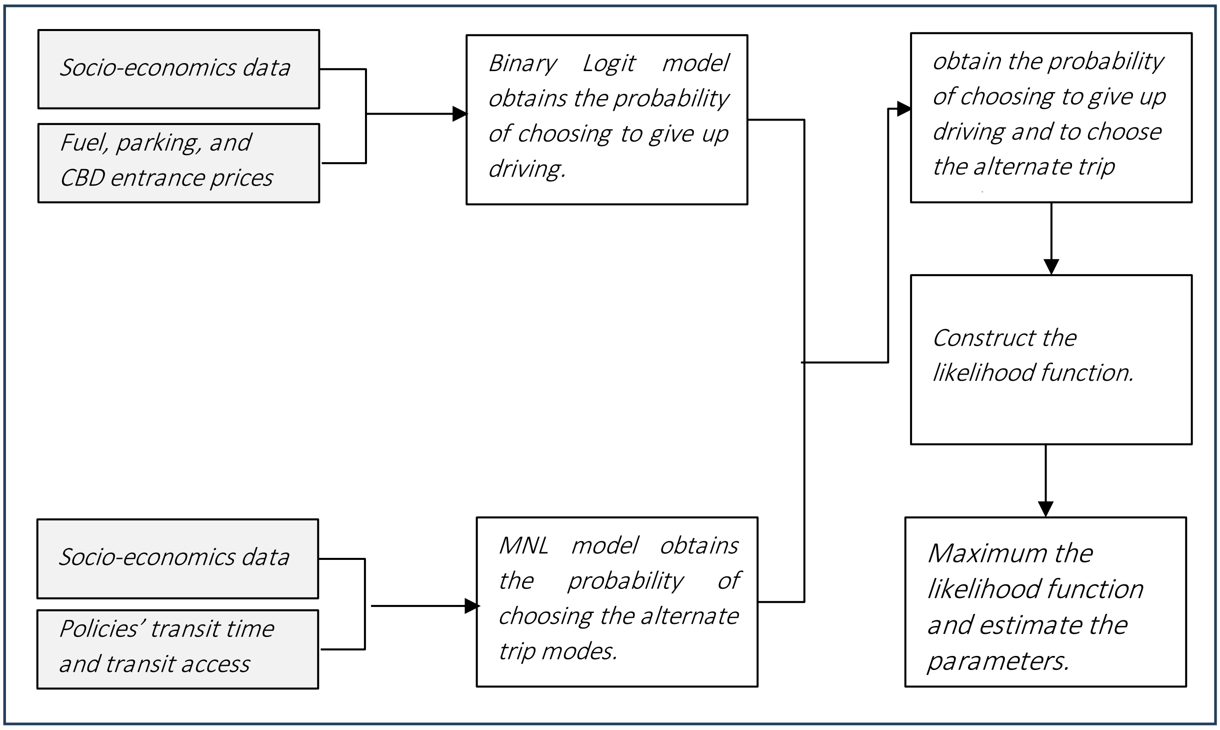

Figure 1. The Structure of the Methodology

5. Results

5.1. General Discussion

As mentioned above, believing the difference between mode choice and change mode decisions copula-based joint model is used to test the idea. First, an independent model of mode change and mode choice decision was estimated to serve as the starting point for the joint model estimation and also to compare with the final joint model. Five different copula structures were applied (FGM, Frank, AMH, Gumbel, and product copula) to consider the correlation between the unobserved factors of the two models. Among them, three ended in acceptable models. General information about these five models is presented in Table 4.

Table 4. General Information about Models with Different Copulas

Copula	Acceptable range for (θ)	Dependence parameter	Acceptable model	Log-likelihood
Frank	(-∞,∞)	3.271[a]	✓	-2718.120
Gumbel	[1, ∞)	1.617[c]	✓	-2724.418
Product	-	-	✓	-2736.071
FGM	[-1,1]	2.751	×	-2728.621
AMH	[-1,1]	2.411	×	-2721.994

[a] Significant at 1% level.

[b] Significant at 5% level.

[c] Significant at 10% level.

According to the higher maximum likelihood value of the Frank copula, this structure is presented in the following part.

The final model identifies the factors that have simultaneous effects on the modal shift from a private car and choosing a substitute mode. It also shows the distinct variables for each stage. Concentrating on common factors, policymakers can use more effective policies to increase both the probability of a modal shift from the private car and choosing more sustainable travel modes. Paying attention to distinct variables helps them to predict the effectiveness of each strategy on giving up the driving or choosing a specific choice more accurately.

As shown in Table 6 the dependency parameter (θ) of the model (3.271) is significant at 1%. The log-likelihood of the final model with 55 estimated parameters is -2718.120 and ρ^2_{adj} is 0.158.

Changing the private car is modeled using binomial logit formulation. It is assumed that the error terms of the utility functions have identical and independent Gumbel distributions. Multinomial logit formulation is taken for choosing a substitute mode model. In this research, Frank, Gumbel, FGM, AMH, and Product copula were used to reach a better-fitted model. The general information about models with different copulas can be found in Table 4. As the copula with the greatest log-likelihood and the dependence parameter in the acceptable range is the best copula, Frank copula is chosen to be presented in this paper.

Using the literature as a guide, different kinds of variables were used to model both the decisions to give up driving and to choose a new travel mode. Five policy measures, some work trip characteristics, and several socio-economic aspects were tested. Among them, some seem to be ineffective. Table 5 shows the variables that appeared significant in the final model.

As mentioned earlier, this study aimed to find the common effective variables on choosing to leave driving a private car and to pick a new transport mode as well as to present the best copula model for these two related decisions.

Table 6 demonstrates the common variables of the two models and the model's fit information.

Moreover, Table 7 shows the uncommon variables affecting the two decisions.

5.2. Impact of Variables Common to Both Choices

As shown in Table 6 among those variables common on both giving up the private car and choosing a new travel mode choice, nine have the same signs and two have opposite signs. The negative sign of the variable ACCW2, which is a dummy to show that the respondent needs to use a taxi to access a transit station, in the utility function of giving up driving and choosing transit, suggests that this access way causes disutility for both choices. In other words, relocating the transit stations in a way that fewer people need to use taxis to get to them; either by using the private car to park and ride, or walking to the station, will make both choices of giving up the car and choosing transit more acceptable. The negative common sign of CARA shows that people who are using prepaid CBD entrance permissions are less likely to give up driving in response to a hypothetical bundle of TDM strategies; moreover, if they do so transit has a lower chance of being accepted by them among the five new options. If using transit as a sustainable and more efficient choice is desired, policymakers should take omitting the yearly prepaid CBD entrance permissions into account and make more benefits by changing them to daily passes.

Table 5. Description of Variables

No	Variable	Description	Type or Value
1	ACCT	Transit access time	actual time, a 33% decrease in actual time
2	ACCW2	Access way to transit station: taxi	1 if yes; 0 otherwise
3	ACCW3	Access way to transit station: walk	1 if yes; 0 otherwise
4	AGE1	Age less than 30 years	1 if yes; 0 otherwise
5	AGE2	Age between 31 and 50 years	1 if yes; 0 otherwise
6	CARA	Has prepaid permission to enter CBD	1 if yes; 0 otherwise
7	CBD	House located in CBD	1 if yes; 0 otherwise
8	CBAWK	Need a car before or after work	1 if yes; 0 otherwise
9	CCARR	Need a car to carry things	1 if yes; 0 otherwise
10	CDUWK	Need a car during work hour	1 if yes; 0 otherwise
11	CGIRI	Need a car to give rides to others	1 if yes; 0 otherwise
12	CLSEC	Uses car because of the Low security in transit	1 if yes; 0 otherwise
13	Const.	Constant term	continuous
14	CTVAR	Uses car because of the trip time variation in transit	1 if yes; 0 otherwise
15	DIS	Home to work distance (km)	continuous
16	EDU1	Some colleges or less	1 if yes; 0 otherwise
17	EDU2	Bachelor’s or master’s degree	1 if yes; 0 otherwise
18	EDU3	PhD or MD	1 if yes; 0 otherwise
19	EMP1	The respondent is a freelance worker	1 if yes; 0 otherwise
20	EMP2	The respondent is an employee	1 if yes; 0 otherwise
21	EMP3	The respondent is a student	1 if yes; 0 otherwise
22	ENTF	CBD entrance toll ($ per day)	5, 10, 15
23	FGP	Additional fuel needed beyond coupons	Ordinal variable 0 to 4
24	MALE	Male	1 if yes; 0 otherwise
25	HHDL	No. of driver’s licenses in household	NA
26	HHN	No. in household	NA
27	MAR	Married	1 if yes; 0 otherwise

No	Variable	Description	Type or Value
28	NOC	No. of cars in household	NA
29	PAR1	Mostly parks the car in private parking	1 if yes; 0 otherwise
30	PAR2	Mostly parks the car on-street paid fee	1 if yes; 0 otherwise
31	PAR3	Mostly parks the car on-street for free	1 if yes; 0 otherwise
32	PARKF	Parking fee ($ per day)	1.20, 2, 3
33	TT	Decrease in transit travel time (percent)	0, 20, 33

Note: No. = number; NA = not applicable.

Table 6. Model Results for Variables Common to Both Choice Models

Var.	Give up the private-car	Transit	Taxi	Rideshare	Walk & other	Cycle
	Coef.	Coef.	Coef.	Coef.	Coef.	Coef.
Same Signs						
ACCW2	-4.447[c]	3.273[a]				
CARA	-3.293[a]	-5.262[c]				
CGIRI	0.021[c]	1.290[b]				
DIS	1.030[b]	1.028[a]		0.858[a]		
EDU1	3.723[a]	0.993[a]				
EMP1	7.551[a]				0.141[a]	
EMP3	0.741[c]			0.547[b]		
FGP	-5.145[b]		-2.399[c]			
HHN	5.499[c]			0.763[a]		
NOC	-1.836[a]			-6.393[a]		
Opposite Signs						
CBD	2.938[a]	-0.893[b]				-0.913[a]
MALE	-2.399[a]		0.147[a]			
Dependency parameter (θ)			3.271[a]			
Log-likelihood at convergence			-2718.120			
Log-likelihood at zero			-3293.003			
Log-likelihood at market share			-3293.003 add please and the ρ2			
ρ^2			0.175			
ρ^{2adj}			0.158			
Number of estimated parameters			55			
Sample size			3642			

Note: Coef.= Coefficient.
[a] Significant at 1% level.
[b] Significant at 5% level.
[c] Significant at 10% level.

People who currently drive their private cars to work because of their need to give rides to others, CGRI, seem to be good cases to give up driving and use transit instead. The positive sign of the DIS variable suggests that while facing the described package of policies, the more the distance between the home and the workplace of the respondents, the more the probability of leaving the driving and choosing to rideshare. The same effect is recognized for having an education level of some college or less (EDU1). Furthermore, final results show that freelance workers are more likely to quit driving and to choose the choice of walking or to change the time of their work trip or their workplace. This conclusion seems rational. Also, students are likely to stop driving, but their substitute choice is to use rideshare. As shown in Table 6, people who currently use more fuel than the monthly coupon, which has a lower price, are less likely to choose the not-driving choice and if they choose this option, using a taxi is barely probable for them.

As the final model reveals, living in households with more members increases the utility of giving up driving while facing the hypothetical scenarios of different levels of TDM policies. On the other hand, as could be expected, the more the household number the more probable a respondent chooses to rideshare. On the contrary, when one lives in a household with more cars, leaving the driving and choosing to rideshare is less expected.

Table 6 also shows that living in the CBD has a positive effect on giving up driving. This could be in response to the availability of and good access to other travel mode choices in this area. However, living in this neighborhood has a negative effect on transit use; maybe because of the good access to other choices, like taxis and the opportunity to access the destination on foot, in this area and the small size of the CBD (compared to the whole city) that both make their trip less attractive with transit. This variable also has a negative sign in the utility function of the cycle. This might have happened because of the higher density of population and buildings in this area and the absence of bike roadways besides the compact roadways and sidewalks. Being a male has a negative impact on the decision to quit driving while it affects the choice of a taxi positively. In other words, men are less likely to choose not to drive and if they do so, they are more likely to choose a taxi, which is a cheaper choice than a car although yet a convenient one.

Table 7. Variables Distinct to the Change Mode Choice and the New Mode Choice

Var.	**Give up the private-car**	**Transit**	**Taxi**	**Rideshare**	**Walk & other**	**Cycle**
	Coef.	**Coef.**	**Coef.**	**Coef.**	**Coef.**	**Coef.**
Const.	1.261[a]	-3.436 [c]		-7.051[a]	-1.446[c]	4.907[a]
ACCT		-1.753[b]	0.845[b]			
ACCW3		0.982c			1.068[c]	0.190[c]
AGE1		1.919[c]				
AGE2	1.524[b]					
ENTF	2.851[a]					
HHDL		-0.016[a]		-0.698[a]		
MAR			-2.077[a]		2.026[b]	
PAR1			-2.153[c]			
PAR2			-0.744[c]			
PARKF	0.793[c]					
CBAWK	-3.723[a]					
CDUWK		-1.072[b]	-0.296[a]			
CCARR				-0.022[a]		
CTVAR		0.020[a]				
CLSEC		-0.881[b]		-4.554[a]		
TT		3.627[c]				

Note: Coef.= Coefficient.

[a] Significant at 1% level.

[b] Significant at 5% level.

[c] Significant at 10% level

5.3. Impact of Variables Distinct to the Change Mode Choice and the New Mode Choice

Among the effective variables on the choice of not driving, two policy measures are displayed. As expected, TDM policies to discourage driving appeared with positive signs. It means that the necessity to pay a CBD entrance toll (ENTF) has a direct effect on preferring not to use a private car. A parking charge (PARKF) seems to impact the decision the same way. As could be anticipated, the coefficient of the former is more than the latter due to its higher price. The fuel price did not appear effective in the final model, which suggested that raising the fuel price could not make the use of private cars less. At the time of the data gathering, the actual fuel price was $0.1/L and the model's results indicated that even raising the price to about eight times could not affect the car use. The fuel price raised to $0.7/L soon after the data gathering and was constant for the next four years. The official consumption statistics reveal that the daily gasoline usage in the country increased by almost 13.5% in this period [NIOC, 2014].

As shown in Table 7, being in the age group between 31 and 50 years (AGE2) has a positive effect on choosing to give up driving to work. The final model also reveals that, as expected, needing a car to accomplish some tasks before or after the work-time (CBAWK) has a significant negative effect on choosing not to drive. In other words, people who need their car not only for the commute trip but also to do some other things are less likely to give up driving.

Paying attention to the alternate mode choice model it is recognized that final transit utility variables disclose that both the improved access time (ACCT) and the decrease in transit travel time (TT) strategies have significant effects on the choice of the transit. So, the results suggest that implementing these two policies may increase the probability of choosing transit. It should be taken into account that the access time that is used in the modeling process is the improved access time, and according to the obvious negative effect of access time on transit, the negative sign of this coefficient is expected. On the other hand, the transit time used in the models shows the percentage of the decrease in the travel time with transit, which is expected to be positively significant. The positive sign of ACCT in the taxi utility function reveals that as anticipated the more the access to transit station takes the more the taxi choice becomes attractive.

The positive sign of ACCW3 in transit utility function implies that people who reported walking as their access way to the transit station seem to choose transit more. According to this result, not only the transit access time but also the transit access way, significantly affects the utility to choose transit. The final utility function of the transit also shows that being less than 30 years old (AGE1) has a positive effect on transit use. The negative sign of CDUWK reveals that the need for a private car during work hours makes transit less acceptable.

The final results imply that the number of household driver license holders (HHDL) has a negative sign in both transit and rideshare utility functions. In other words, in families with more drivers using transit or sharing a car with others is less attractive, as expected. The negative sign of the MAR variable in choosing a taxi suggests that married people are less likely to choose this mode. On the other hand, being married has a positive sign in the utility function of the 'walk and other' choice. Both signs suggest that married people might be more sensitive about expenses.

The negative signs of both PAR1 and PAR2 in the taxi utility function indicate that for people who currently park their cars for free, either in private parking or on-street, a taxi is not a preferred choice when they face a bundle of TDM policies.

Needing the car during work hours (CDUWK) makes both transit and taxi less attractive. Also, the need to carry things (CCARR) has a negative sign in the rideshare utility function. People who currently use private cars because of the variation in transit travel time (CTVAR) prefer transit more while facing an improved one. But for commuters who choose to drive because of the lack of security in transit (CLSEC) the improvement of the transit in travel time and access time is not enough motivation to choose transit. The security issue has a negative impact on the rideshare utility function as well. It seems that the security problem is interconnected with the absence of privacy in the vehicles.

5.4. Correlation Parameter

According to Table 6, the estimated copula correlation parameter is positive and significant; which indicates that there is a positive correlation between the unobserved factors of both choosing to give up driving and adopting a new travel mode (i.e. the error terms ε_q and υ_q). In other words, while trying to choose between continuing to use their regular travel mode (i.e., a private car) and giving up driving, respondents also have a glance at other modes' characteristics. On the other hand, choosing between modes rather than the private car won't take place without choosing to give up driving in response to TDM policies. This positive correlation means that some similar unobserved variables increase the utility of both giving up the private car and choosing a substitute mode. For instance, environmental concerns and lack of individual interest in driving might be among these variables.

6. Conclusion

In this study, a joint structure for the driver's change mode shift decision-making was tested. The commuter’s first decision is to change his/her current travel mode or not, and the second is to choose a different mode (among those presented if he/she chose 'the not to drive choice' in the previous step). The experiment took place under a series of hypothetical situations in which different levels of five TDM policy measures were implemented in a survey conducted in May 2010 in Tehran. Different socio-economic and work trip traits were examined as well. Testing different copulas for the joint structure, Frank copula seems to give the best fit. The final model specifies the significant observed variables, while the correlation parameter gives the coefficient for the unobserved factors of both models. The common variables on both decisions conduct actions that are effective in pulling commute drivers from their cars and pushing them to other more sustainable travel modes.

According to model results, two pull policies (CBD entrance toll and parking fee) seem to be effective in motivating driver commuters to shift away from driving. On the other hand, raising the fuel price does not show a significant impact. Besides, the study reveals that decreasing transit travel time and transit access time have significant effects on mode choice by making transit more acceptable. Based on the actual impact of these four policy measures among the five used in this study, which ended in almost 76% of respondents choosing a new mode rather than their regular private car, using both pull and push TDM strategies is suggested. Moreover, using these four tested policies is recommended as the first candidates.

Moreover, as model results suggest, people who use a taxi to access a transit station, are more apt not to shift away from driving. It also makes the transit choice less attractive for people who choose not to drive. In fact, transportation planners might come to a new allocation of transit stations in which as many as possible people could reach the stations either on foot to near stations or in their private cars to stations with good parking facilities nearby.

A comparative study of two sets of a stated preference and a revealed preference data might display more details about the decision-making process. Also, a gender-based joint model could help to understand the effective parameters of each gender's mode choice better. The more specified the impressive factors are known, the better the policymakers choose effectual strategies. Using psychological and environmental variables could be an illustrative way. Further studies might target 'habit' as an obstacle to changing mode and suggest how to overcome this issue to make TDM policies more effective.

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Research Paper

Capacity Analysis and Level of Service Estimation for a Section of the Highway Based on HCM2016 (Case Study: Shahid Sadr Highway Class-Bridge)

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Abstract

Annually, traffic problems ranging from congestion, air and noise pollution, abundant accidents, unacceptable increases in travel time, and various types of damages are the advance of most countries, especially in developing countries. Environmental pollution, casualty, and financial costs, as well as accidents, increased fuel consumption, the extent of resources allocated to build the network, and the huge cost of construction of various transport systems, as well as other side costs, destroy large amounts of human and economic resources in the country. It becomes. Therefore, the prediction of traffic for a pre-construction route as well as analyzing and estimating the capacity and prediction of future demand, due to the expansion and improvement of the network and preventing the creation of problems developed from increasing demand and lack of facilities, and can have problems The existing network minimizes the country's roads. Functional criteria are determined by defining the concept of level-of-service (LOS). In this research, the analysis of highway capacity was obtained using the data from the Shahid Sadr class-bridge in Tehran, based on the 415, HCM2016 regulations and headway methods, and then the results were compared using Synchro and Aimsun software.

Keywords: Capacity Analysis, Level of Service, Traffic Performance Index, HCM2016 Regulation

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1. Introduction

As we know, land transportation is the most in-demand among other modes of transportation. Road transport is of great importance in all countries in terms of both passenger and freight traffic. As the demand for road travel is increasing day by day, the need to pay attention to the expansion of the land transport network is of particular importance. Therefore, forecasting the demand for a route before construction, as well as predicting the future traffic volume and current capacity of an axis, play a key role in expanding a country's road network. since the invention of the automobile, man has always wanted to create facilities and regulations to regulate traffic. The increasing number of vehicles has occupied the minds of traffic engineers in order to facilitate transportation and prevent waste of costs and time. As traffic issues become more complex, the use of computers to control and manage traffic is becoming more common day by day, and among these, computer simulation as a powerful and efficient tool is becoming more considered and used by engineers.

Estimation level of service (LOS) and highway capacity are important and influential factors in traffic volume, delay, and volume of traffic. Thus, examining and identifying the relationship between these two important parameters can guide decision-makers in designing policies in different ways. A lot of users' time is wasted in traffic every day in cities, especially in a metropolis like Tehran; In addition to the time spent in traffic, we can point to other problems such as higher fuel consumption, air and noise pollution, and lower level of user satisfaction, which put a lot of costs on users as well as the government and decision-making institutions.

The LOS is a measure of quality on the roads that shows the practical traffic conditions and the level of drivers' satisfaction with these conditions. This criterion depends on factors such as speed, travel time, freedom, having enough space to maneuver, and road safety. LOS are classified into 6 categories from A to F. In a way, LOS A represents the best conditions and level F represents the worst traffic conditions. The maximum flow that can cross the road at any LOS (except level F) is called the traffic flow. Thus, each facility according to each LOS (from A to E) has 5 currents, which is the maximum hourly current that persons or vehicles can reasonably expect to cross a point or crossing line or rider in a period of time. On the other hand, two facilities with the same LOS may be different from two facilities with two different LOS. This has to do with how the LOS is defined. Note that the LOS should be introduced in terms of indicators that can be seen and touched by drivers. So, traffic volume, as a benchmark on the road that is not understood by drivers and passengers, will never be used as a benchmark for LOS.

Road capacity is defined as the amount of maximum passing of vehicles. In traffic engineering, the passage of vehicles or pedestrians from the facility is considered. Road capacity can be defined as the maximum volume of traffic crossing the road section, while with the addition of one unit of traffic volume, congestion, and obstruction can occur. On the other hand, due to variable weather conditions or traffic control conditions, there will be no unit value for road capacity and this value is introduced as a random variable that follows a specific statistical distribution. This indicates the possible nature of the capacity. Capacity doesn’t remain constant even under ideal conditions. The reason for this is the existence of immeasurable variables such as the behavior of drivers or vehicles. Thus, it is usually not possible to measure the ideal capacity and therefore to accurately estimate its statistical distribution.

In addition to the stochastic nature of capacity, various definitions have been proposed according to the purpose of the studies for road capacity. Capacity for design is a unit value that is usually derived from random distribution functions and represents the maximum volume passing through a section of the road with a certain probability and with certain environmental conditions. This value is used for road planning and design and can be calculated from indirect experimental methods such as highway capacity instruction methods. Strategic capacity is a value that is usually derived from random distribution functions and represents the maximum volume of traffic that a road section can pass. This value is used to allocate traffic and simulations This capacity or distribution is calculated based on traffic flow information and calculated by static models. Execution capacity, on the other hand, is the amount of capacity that represents the maximum volume that actually crosses the road. This value can be used for short-term traffic estimates and can be calculated based on direct experimental methods with the help of dynamic capacity models.

It is necessary to explain about the two regulations (415 Code and HCM2016) that have been used for analysis in the research.

1.1. Highway Geometric Design Code (No.415)

The Highway Geometric Design Code No. 415 refers to a specific set of guidelines and standards for the design of highways. These codes typically include specifications for various elements such as alignment, cross-section, sight distance, intersections, and other geometric features.

The specific details and requirements outlined in Code No. 415 may vary depending on the country or jurisdiction that has established it. It is important to consult the relevant transportation authority or agency responsible for highway design in your area to obtain the most up-to-date version of the code.

Some common topics covered in highway geometric design codes include:

- **Horizontal Alignment:** Guidelines for determining the curvature and alignment of the road, including minimum radius of curves, superelevation (banking), transition curves, and horizontal clearances.
- **Vertical Alignment:** Specifications for vertical curves, grades (slopes), crest and sag vertical curves, sight distance requirements, and vertical clearances such as overhead bridges or tunnels.
- **Cross-Section Elements:** Standards for roadway width, number of lanes, shoulder widths, median design (if applicable), drainage provisions like ditches or culverts, and pavement markings.
- **Intersections:** Design criteria for various types of intersections such as signalized intersections, roundabouts, and interchanges (grade-separated junctions), including lane configurations, turning radii, sight distance at intersections, etc.
- **Access Management:** Guidelines for controlling access points along highways to ensure safe traffic flow and minimize conflicts with adjacent land uses.
- **Pedestrian and Bicycle Facilities:** Requirements for providing safe accommodations for pedestrians and cyclists along or across highways through sidewalks, crosswalks, bike lanes, or shared-use paths.
- **Safety Considerations:** Standards related to safety features like guardrails/barriers placement based on crash severity levels; signage requirements; visibility considerations; lighting provisions; etc.

It is important to note that these are just general topics that may be covered in a highway geometric design code, and the specific details and requirements can vary significantly depending on the jurisdiction.

1.2. Highway Capacity Manual (HCM) 2016

The Highway Capacity Manual (HCM) is a publication that provides guidelines and methodologies for evaluating the capacity and operational performance of various types of highways and transportation facilities. It is widely used by transportation engineers, planners, and researchers to analyze and design transportation systems.

The HCM covers a wide range of topics related to highway capacity, including traffic flow theory, level of service analysis, intersection design, freeway operations, pedestrian and bicycle facilities, transit operations, and more. It provides detailed procedures for estimating traffic volumes, analyzing congestion levels, determining the capacity of different roadway elements, and evaluating the effectiveness of various operational strategies.

The manual includes several chapters with specific methodologies for different types of facilities such as urban streets, signalized intersections, roundabouts, freeways, toll plazas, etc. It also provides guidance on how to incorporate emerging technologies and innovative practices into transportation planning and design.

Overall, the Highway Capacity Manual serves as a comprehensive resource for professionals involved in transportation planning and engineering to assess the performance of existing highways or plan new ones in an efficient and effective manner.

The main difference between the 2016 version of the Highway Capacity Manual (HCM) and previous versions is the inclusion of new methodologies and updated research findings. Some key differences include:

– **Incorporation of Freeway Facilities:** The 2016 HCM includes a comprehensive chapter on freeway facilities, which was not present in previous versions. This chapter provides guidelines for analyzing and evaluating freeway operations and capacity.

– **Multimodal Analysis:** The 2016 HCM introduces a multimodal approach to transportation analysis, considering various modes of transportation such as pedestrians, bicycles, and transit vehicles. Previous versions primarily focused on vehicular traffic.

– **Performance Measures:** The 2016 HCM emphasizes the use of performance measures to evaluate transportation systems' effectiveness and efficiency. It provides guidance on measuring various parameters like travel time reliability, delay, and level of service.

– **Software Tools:** The latest version incorporates new software tools that facilitate analysis and evaluation processes. These tools help practitioners apply the methodologies described in the manual more efficiently.

– **Updated Research Findings:** The 2016 HCM incorporates recent research findings related to traffic flow theory, capacity estimation, signalized intersections, roundabouts, pedestrian facilities, transit operations, and other relevant topics.

Overall, the 2016 version of the Highway Capacity Manual reflects advancements in transportation engineering practices and provides more comprehensive guidance for analyzing different types of roadways and modes of transportation.

2. Literature Review

Issues related to road capacity and level of service have gained attention and have been extensively studied recently due to the increased traffic congestion in the urban road network. Afshin Shariat (2010) studied the alternative criterion of the performance index of suburban two-lane highways. To determine the service level of two-way two-lane routes, two performance indicators of tracking-time percentage and average travel speed are used. The results of this paper showed that the percentages of the sequence time obtained from the simulation in the software with the alternative index, the percentage of vehicles with a headway of 3 seconds or less are very close to each other. Mohammad Tamnaei et al. (2012) conducted a study to analyze the time distance distribution of vehicles in day and night conditions under heavy traffic flow. The purpose of this study was to evaluate the behavior of drivers to choose the distance during peak hours of day and night traffic. The results show that the log-normal distribution model is a suitable model for fitting the distribution of distances in the overtaking line, while the Gamma distribution model is suitable for fitting the midline distances. Also, the study of the results of the comparison in day and night conditions showed that drivers in the conditions of heavy traffic at night, take safer headway than during the day. Rahimef in 2014, examined the capacity and level of service in the urban transportation network. Traffic flow in this network is plotted based on the O-D matrix. Due to the constant current in the network, if a source request enters the network, it will face a problem. This problem has been investigated in this study. For this purpose, a new formulation and model has been proposed that examines this issue according to the O-D matrix. Velmurugan Senatipati in 2010, analyzed the road capacity assessment of multi-speed routes under heterogeneous traffic conditions using traditional and microscopic simulation models. In this paper, the speed-flow characteristics of different types of multi-lane highways, including four-lane, six-lane, and eight-lane used in plain areas, were investigated. From the collected data, free flow speed profiles and speed flow equations for different types of vehicles for different versions of multi-lane highways have been developed based on traditional and microscopic simulation models, and subsequently, road capacity has been estimated. In addition, the change in behavior of different types of vehicles has been extensively studied and its impact on road capacity on multi-lane highways has been estimated. Subhadip Biswas in 2016 conducted a study to evaluate the level of service on a class 1 arterial route in Calcutta, India. For this purpose, LOS criteria were performed based on field data obtained from an urban hexagonal arterial in the city. The free-flow speed (FFS) of several vehicle categories was calculated and it was found that the FFS varies considerably depending on the vehicle type. Smaller vehicles (excluding two-wheelers) have higher FFSs than larger vehicles. Compared to other types of vehicles, the results of this study showed that light commercial vehicles (LCV) and trucks behaved more consistently in low-density traffic conditions. To evaluate the LOS in urban arterials, the percentage of speed reduction (PSR) of FFS was selected as the functional indicator of traffic flow. An increase in PSR indicates a decline in the quality of transit services. In addition, the PSR value increases with increasing v/c ratio. His approach obtained the behavior of six groups of vehicles created using the K-mean clustering method that is compatible with PSR data. When the percentage of deceleration seems to be more than 50%, the performance of the traffic flow according to the LOS criteria based on PSR reaches the worst level of service level (F). The proposed method in this study for the analysis of LOS standards for urban arterials in different places and useful conditions provides acceptable results. B.R. Marwah and Bhuvanesh Singh (2018) sought to classify the degree of service for urban traffic conditions that are varied. Journey speeds of vehicles and motorized two-wheelers are taken into account while determining the LOS, as well as concentration and road occupancy. The four LOS are characterized based on the simulation results of the benchmark road and traffic composition (Level A). The LOS categorization developed in this study will be useful in identifying shortcomings in an urban road system and planning alternative improvement approaches to achieve the desired LOS. The capacity of the model to replicate urban diverse traffic flow conditions is clearly demonstrated by the examination of simulation data. Matti Pursula in 2019 conducted a study to estimate the level of traffic flow service on two-lane highways in Finland. The results are consistent with USA standard data on the flatness and linearity of flow-speed curves, as well as the capacity of two-lane highways. In HCM, deceleration appears to be faster than actual traffic on Finnish highways. The length of car groups and the forward distribution rates of car groups were considered in a simple study. A closer look at the progressive distributions of cars on the Luwal Al Highway, as well as statistical studies on the length distribution of car categories, showed that the assumptions were not valid. The simple theory, however, provided simple connections that were useful in examining the fundamental links between platoon percentage, mean platoon length, and flow speed. The percentage of vehicles moving shorter than 5 seconds was used as the approximate percentage of delay. The results of this study follow the HCM standard, although variations between Finland and HCM based on USA traffic conditions may have been used due to variance in actual values of delay-time and approximation.

3. Data Description

In order to obtain the LOS of Sadr Highway based on the source of this research, various parameters of the highway must be collected. This information is listed below:

- The width of the crossing lines
- Obstacle distance from the right edge of the highway
- Density of ramps. (Density of ramps are number of ramps entering and exiting the highway in the range of 4.8 km before and 4.8 km after the middle of the base section of the highway)
- Equivalent traffic rate (veh/hr/ln)
- demand flow rate under equivalent base conditions
- Peak hour factor (PHF)
- Number of lines
- Adjustment factor for the presence of heavy vehicles
- Adjustment factor for the presence of occasional or non-familiar users of a facility
- Percentage of heavy vehicles and buses on the route
- Percentage of recreational vehicles on the route
- Passenger car equivalence on heavy vehicles
- Passenger car equivalence on recreational vehicles
- Density
- Average speed

Because the measured case sample should be a good indicator of the condition of the passage, it shouldn’t be at the beginning and end of the week, so Sunday was found to be suitable for the census. It was also considered to conduct surveys in sunny weather to prevent the effects of weather on drivers' behavior. Video recording will be used to obtain effective parameters at the level of the crossing service, and some parameters were also measured on site, such as the width of the crossing lines and the distance of the obstacles from the right margin of lines. the filming will start when the volume of the crossing is very small (less than 1000 (veh/hr/ln)) and the filming will continue until finds that the vehicle volume its full capacity and may later reach supersaturation. Because Sadr Highway in Tehran has a high volume of vehicles volume from the early morning hours, in May 2021, it was decided to start the census from 5 A.M. to obtain FFS and continue until 10:30 A.M. to include the peak hours of traffic. Also, when there is the highest volume of traffic on one side of Sadr Highway in Tehran, there is a small volume of traffic on the other side, and the speed of vehicles can be measured in this approach and compared to the speed of vehicles at 5 A.M. If these speeds are inconsistent, it is clear that the FFS of vehicles depends on the brightness of the sun in addition to the lighting of the route, and if the speeds are the same, the difference in lighting between 5 A.M. and 8 A.M. can be ignored.

Due to the fact that it is not possible to create a bottleneck in Sadr highway in Tehran to obtain the capacity from direct methods, the capacity analysis was selected based on the Greenshields curve and the time interval of vehicles methods, and since HCM is one of the most reliable sources for determining the level of road service. As mentioned, in this research, using HCM 2016, the service level of Sadr highway in Tehran city has been measured in the basic stages (away from the effects of entrance and exit ramps and the combination of entrance and exit ramps) and possible differences in the speed chart. Check the traffic

3.1. Volume of Traffic

To investigate the traffic effects on Sadr highway, 5 hours of counting vehicles were taken in the morning in the period from 5:30 to 10:30 A.M and the analysis of the obtained statistics indicates the peak time in the area is between 8:00 and 9:00 A.M. Figure (1) shows the equilibrium volume chart of the East-West approach of the mentioned range in the period of 5:30 to 10:30. According to the chart in below the volume of the peak hour is equal to 5838 vehicles.

Figure (2) shows the volume of passenger car equivalence of the East-West approach of the Sadr class-bridge highway between Kaveh Boulevard and the entrance of Niayesh tunnel at the peak hour.

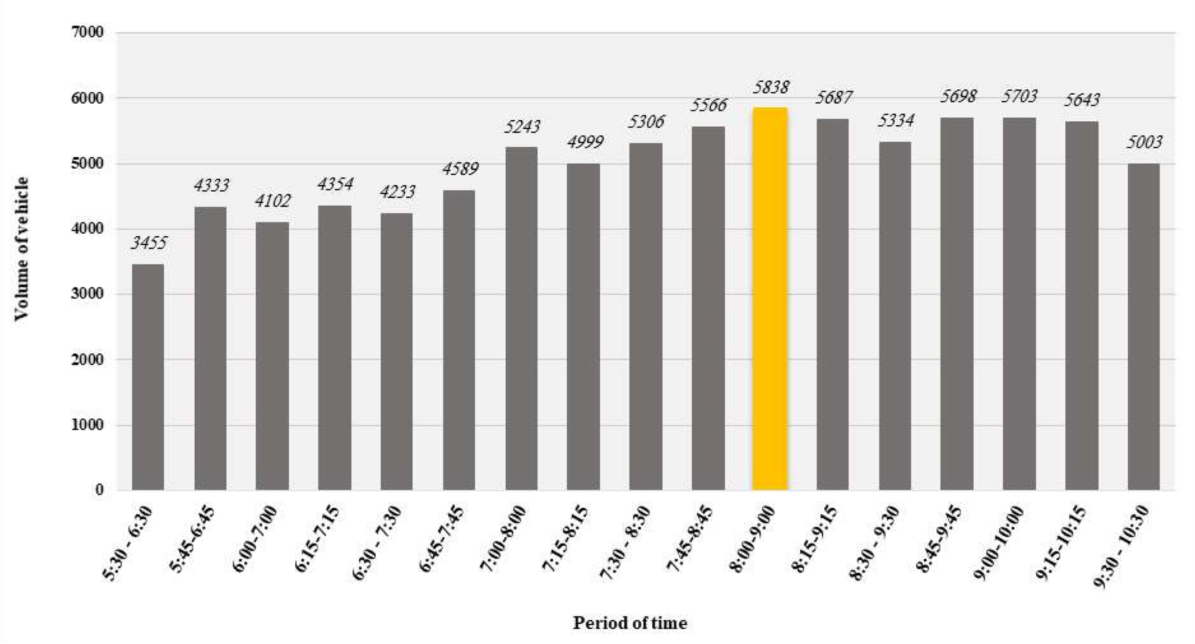


Figure 1. Passenger car equivalence of east-west approach of the Sadr highway between Kaveh Boulevard and the entrance of Niayesh tunnel

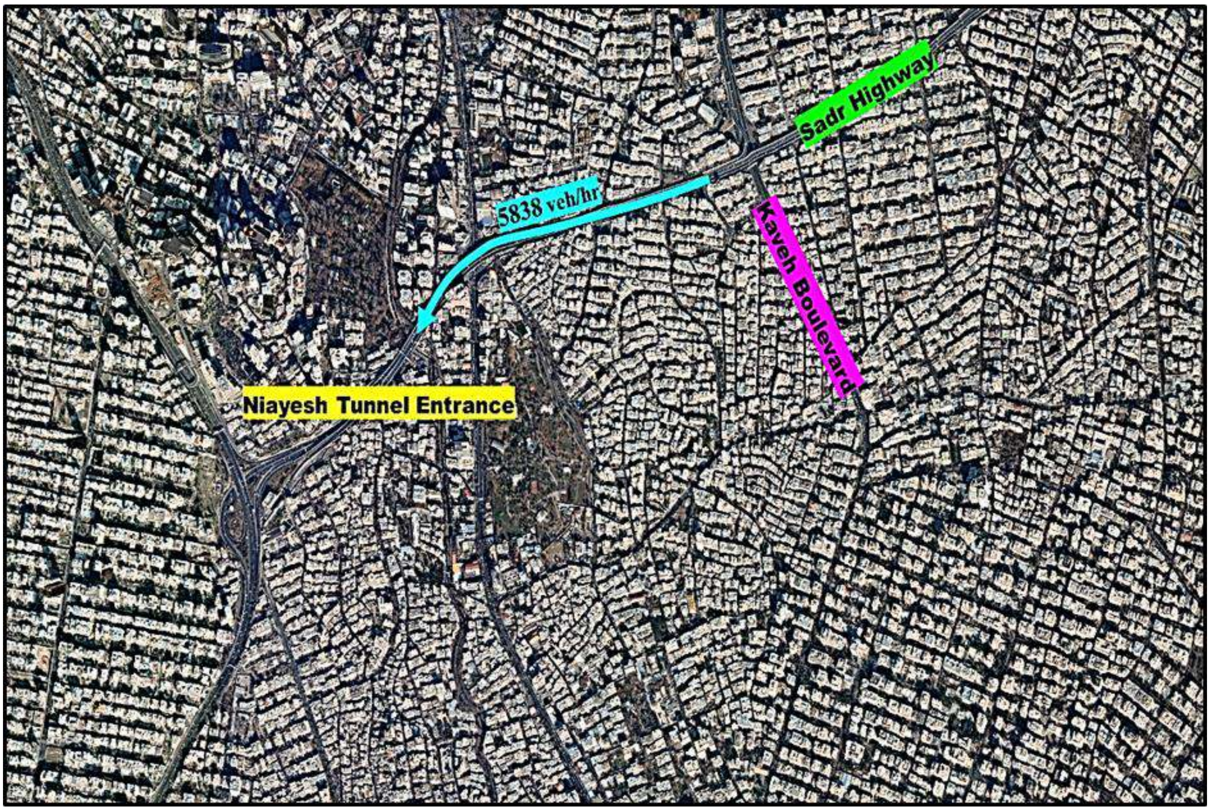
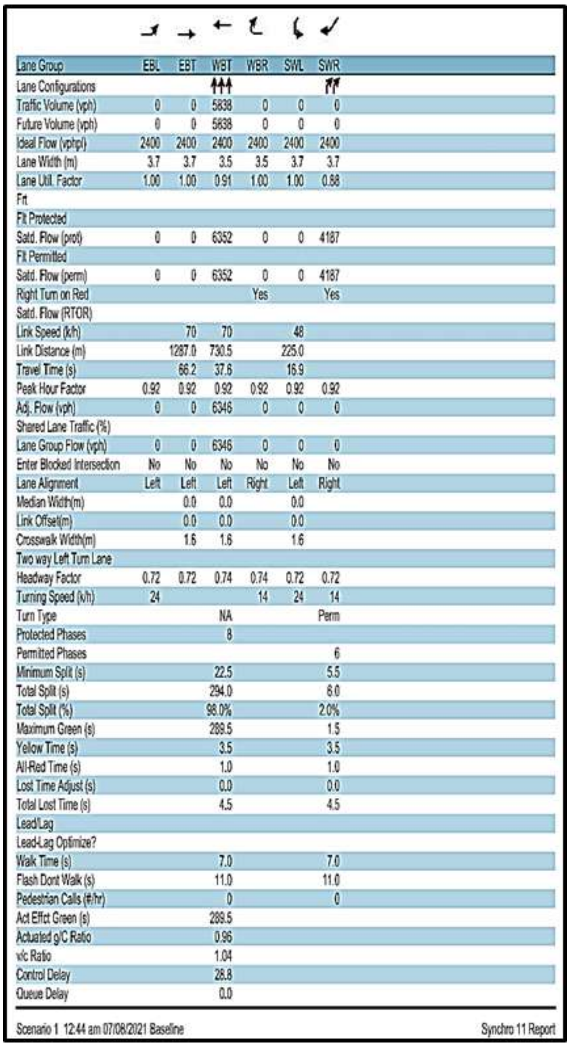


Figure 2. Passenger car equivalence of East-West approach of Sadr highway between Kaveh Boulevard to the entrance of Niayesh tunnel at peak hours

3.2. Network Modeling of the Study Area in Synchro Software

To calculate the traffic index considered in this step, the network of studied routes is modeled in Synchro software. After the simulation, it has prepared software outputs that will be presented below. Figure (3) shows the results extracted from the model in Synchro software.



Lane Group	EBL	EBT	WBT	WBR	SWL	SWR
Lane Configurations			↑↑↑			↱↱
Traffic Volume (vph)	0	0	5838	0	0	0
Future Volume (vph)	0	0	5838	0	0	0
Ideal Flow (vphpl)	2400	2400	2400	2400	2400	2400
Lane Width (m)	3.7	3.7	3.5	3.5	3.7	3.7
Lane Util. Factor	1.00	1.00	0.91	1.00	1.00	0.88
Frt						
Flt Protected						
Satd. Flow (prot)	0	0	6352	0	0	4187
Flt Permitted						
Satd. Flow (perm)	0	0	6352	0	0	4187
Right Turn on Red				Yes		Yes
Satd. Flow (RTOR)						
Link Speed (k/h)		70	70		48	
Link Distance (m)		1287.0	730.5		225.0	
Travel Time (s)		66.2	37.6		16.9	
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92
Adj. Flow (vph)	0	0	6346	0	0	0
Shared Lane Traffic (%)						
Lane Group Flow (vph)	0	0	6346	0	0	0
Enter Blocked Intersection	No	No	No	No	No	No
Lane Alignment	Left	Left	Left	Right	Left	Right
Median Width(m)		0.0	0.0		0.0	
Link Offset(m)		0.0	0.0		0.0	
Crosswalk Width(m)		1.6	1.6		1.6	
Two way Left Turn Lane						
Headway Factor	0.72	0.72	0.74	0.74	0.72	0.72
Turning Speed (k/h)	24			14	24	14
Turn Type			NA			Perm
Protected Phases			8			
Permitted Phases						6
Minimum Split (s)			22.5			5.5
Total Split (s)			294.0			6.0
Total Split (%)			98.0%			2.0%
Maximum Green (s)			289.5			1.5
Yellow Time (s)			3.5			3.5
All-Red Time (s)			1.0			1.0
Lost Time Adjust (s)			0.0			0.0
Total Lost Time (s)			4.5			4.5
Lead/Lag						
Lead-Lag Optimize?						
Walk Time (s)			7.0			7.0
Flash Dont Walk (s)			11.0			11.0
Pedestrian Calls (#/hr)			0			0
Act Effct Green (s)			289.5			
Actuated g/C Ratio			0.96			
v/c Ratio			1.04			
Control Delay			28.8			
Queue Delay			0.0			

Scenario 1 12:44 am 07/08/2021 Baseline | Synchro 11 Report

Figure 3. Synchro software output data

According to the information obtained from Synchro software, the v/c ratio for Sadr Highway at the peak hour is 1.04, and considering that the peak hour volume of 6346 vehicles is equivalent to riding, the capacity of this highway is equal to 6102 vehicles. Due to the fact that this highway has three lanes on each side, the capacity of each of its lanes is equal to 2034 vehicles.

3.3. Network Modeling of the Study Area in Aimsun Software

Aimsun software is a powerful tool in the field of road network modeling and simulation that is used for road network traffic studies.

The purpose of Aimsun is to study and evaluate the road network with respect to traffic studies and counting volumes, and to analyze the capacity of roads, the timing of intersections, and so on. In order to calculate the traffic indicators considered in this step, the network of roads in the study area has been modeled in Aimsun software. The outputs obtained after the simulation in the software are shown below.

Path Assignment | Attributes | Time Series | Validation | Outputs Summary

Copy

Units	Standard Deviation	Value	Time Series
sec/km	[illegible]	[illegible]	Delay Time - Car
veh/km	N/A	[illegible]	Density - Car
veh/h	N/A	[illegible]	Flow - Car
km/h	[illegible]	[illegible]	Harmonic Speed - Car
veh	N/A	[illegible]	Input Count - Car
veh/h	N/A	[illegible]	Input Flow - Car
veh	N/A	[illegible]	Max. Virtual Queue - Car
veh	N/A	۰.۰۰	Mean Queue - Car
veh	N/A	[illegible]	Mean Virtual Queue - Car
	N/A	۰.۰۰	Missed Turns - Car
km/#	N/A	[illegible]	Number of Lane Changes - Car
veh/km/#	N/A	۰.۰۰	Number of Stops - Car
km/h	[illegible]	[illegible]	Speed - Car
sec/km	[illegible]	[illegible]	Stop Time - Car
km	N/A	[illegible]	Total Distance Travelled - Car
km	N/A	[illegible]	Total Distance Travelled (Vehicles Inside) - All
km	N/A	[illegible]	Total Distance Travelled (Vehicles Inside) - Car
	N/A	[illegible]	Total Number of Lane Changes - Car
	N/A	[illegible]	Total Number of Stops - Car
h	N/A	[illegible]	Total Travel Time - Car
h	N/A	[illegible]	Total Travel Time (Vehicles Inside) - All
h	N/A	[illegible]	Total Travel Time (Vehicles Inside) - Car
h	N/A	۰.۰۰	Total Travel Time (Waiting Out) - All
h	N/A	۰.۰۰	Total Travel Time (Waiting Out) - Car
sec/km	[illegible]	[illegible]	Travel Time - Car
veh	N/A	[illegible]	Vehicles Inside - Car
veh	N/A	۰.۰۰	Vehicles Lost Inside - Car
veh	N/A	۰.۰۰	Vehicles Lost Outside - Car
veh	N/A	[illegible]	Vehicles Outside - Car
veh	N/A	[illegible]	Vehicles Waiting to Enter - Car
sec	[illegible]	[illegible]	Waiting Time in Virtual Queue - Car

Cancel | OK | Help

Figure 4. Aimsun software output data

Figure (5) shows the graph of the volume-to-capacity ratio (v/c) for the modeled network in the study area. It is observed that the ratio of volume to capacity on the Sadr Highway is more than one, but its value can not be calculated from the graph. As a result, to calculate the exact value of the volume-to-capacity ratio, the output of the volume-to-capacity ratio diagram is used, as shown in Figure (6). According to the output of Aimsun software, the v/c ratio for Sadr Highway at the peak hour is 1.08, and considering that the peak hour volume of 6492 vehicles is equivalent to riding, the capacity of this highway is equal to 6011 vehicles, which according to The three lanes of this passage on each side have the capacity of each of its lanes equal to 2003 vehicles.

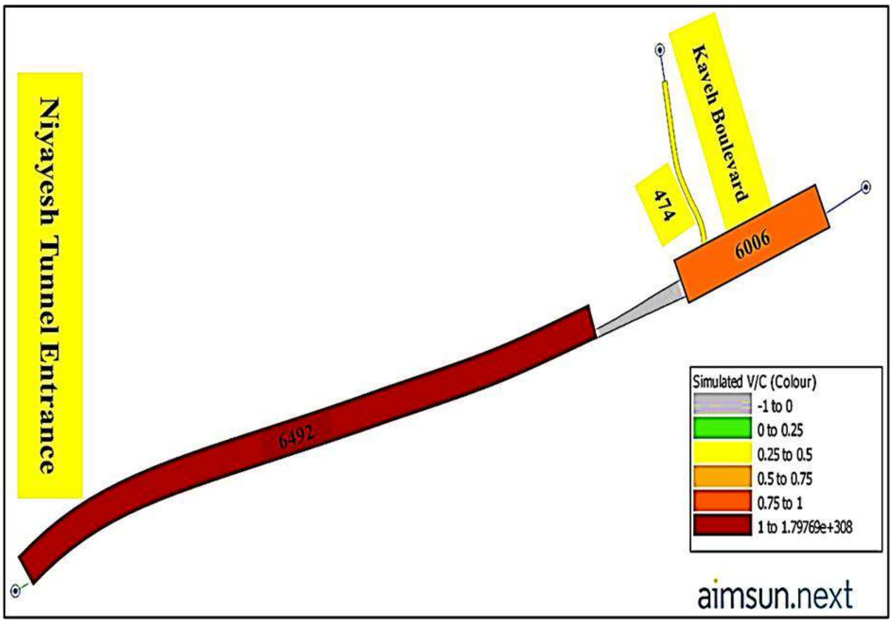


Figure 5. Volume to capacity ratio (V/C) graph for the modeled network in the study area

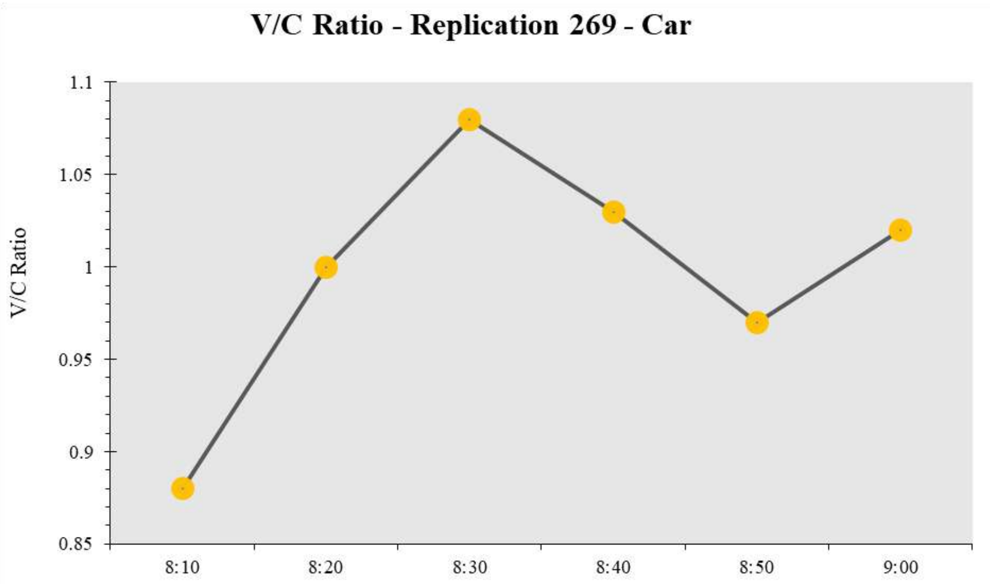


Figure 6. Volume to capacity ratio (V/C) diagram for the modeled network in the study area

3.4. Calculate the Capacity of Sadr Highway Based on Time Headway

The capacity of Sadr Highway was calculated using the relation $C=3600/h_0$. The average headway of vehicles in less than 3.5 seconds on each lane was calculated for 100 vehicles and the results are presented as follows:

- ✓ The average headway of vehicles on the first lane of the highway was 1.9 seconds.
- ✓ The average headway of vehicles on the second lane of the highway was 1.7 seconds.
- ✓ The average headway of vehicles on the third lane of the highway was 1.5 seconds.

According to these results, the capacity of highway lines is 1855, 2041, and 2291 vehicles per hour, respectively.

To obtain the speed-flow diagram, the speed of vehicles is measured. The average speed of non-stop vehicles was calculated every 5 minutes (because the passing rate of vehicles does not change much during this period) and during this period, the number of passenger vehicles, buses, and trucks was counted and the volume was converted to the equivalent transit volume. Table (1) shows the average speed of vehicles and the observed volume of traffic.

Table 1. Volume and speed of vehicles on Sadr Highway

The volume of vehicles on each crossing line	Average speed of observed vehicles
0	70
700	70
1250	63
1500	54
1750	50
2000	39

The free flow speed (FFS) is equal to the average speed of vehicles when the passing volume has no effect on the choice of speed, or in other words, the flow rate is less than 700 vehicles per hour. The free flow speed of vehicles in the measured section was 70 km/h (the average speed of vehicles traveling at a flow rate of less than 700 vehicles per hour was 70 km/h).

By fitting the data in Excel software, Equation (4) is obtained for the recorded data.

$$Q = -1.3321V^2 + 104.64V \qquad (1)$$

According to the concepts of speed, density, and flow relations, to obtain the cross-sectional capacity, the extreme point of the flow-velocity relationship gives the maximum density, or in other words the traffic flow capacity, relative to the speed parameter (V). It is Q_{max}=2055 veh/km/ ln.

Therefore, the maximum capacity will be equal to 2190 vehicles on the line using the quadratic curve model.

The diagram in Figure (7) shows the diagram for the Q_{max} determination relation.

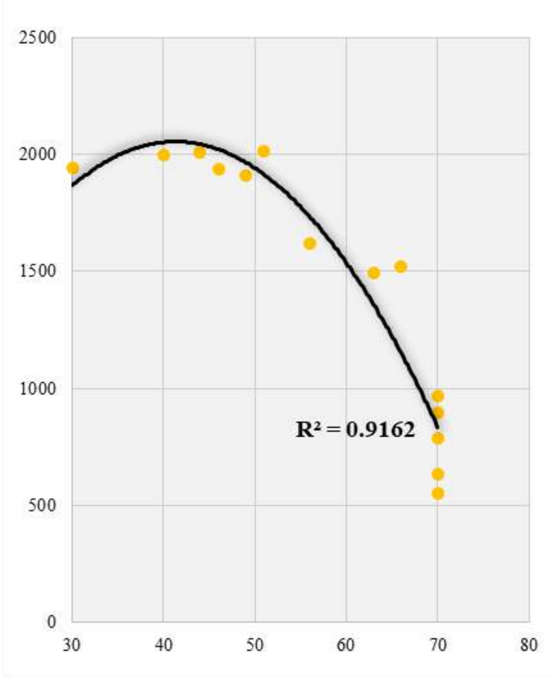


Figure 7. Qmax determination relationship diagram

Figure (8) shows the highway capacity of the study area, which is calculated based on different approaches.

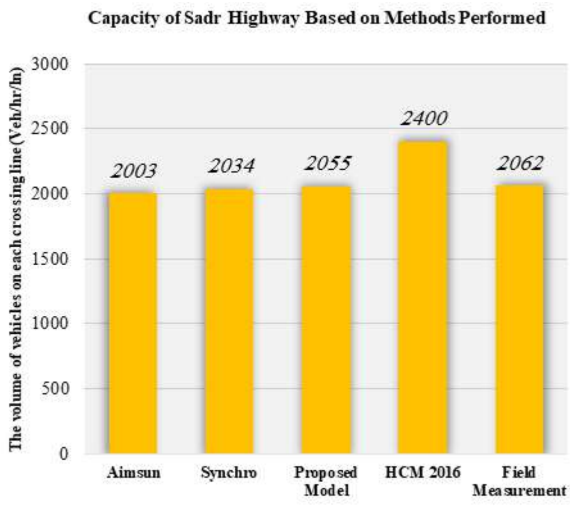


Figure 8. Estimation of capacity based on different methods

The capacity of highway lines in field measurement using the time distance method is 2062 (veh/hr/ln), but the capacity of the highway using the speed-flow diagram HCM2016 is equal to 2400 vehicles per hour per line. The predicted capacity of the crossing in the built model is equal to 2055 vehicles per hour on the line, which is not much different from the time distance method. But since one of the limitations and weaknesses of the HCM method in capacity calculation uses simplified models to estimate capacity, which may not accurately represent real-world conditions. These models assume uniform traffic flow, homogeneous vehicle types, and ideal geometric design features. As a result, the calculated capacities may not reflect the actual capacity of a roadway under different operating conditions. As a result, the output obtained from HCM's method in this study is not very reliable and usable. In the difference between relying on the results of Aimsun and Synchro software and the practicality of their output, If the main focus is on highway capacity analysis, Aimsun would be more suitable due to its comprehensive simulation capabilities. However, if the intersection capacity analysis is at well-marked intersections or smaller-scale projects, Synchro may be more applicable.

4. Conclusion

In this study, in order to analyze the capacity of the basic sections of Iran's highways (a case study of Sadr Highway in Tehran) and analyze the existing relationships between speed and vehicle traffic, traffic flow was recorded by filming a basic section on Sadr Highway and highway capacity This was achieved by using six methods that do not require a traffic density. After the studies, it was observed that the capacity of Sadr Highway lines in field measurement using the time distance method is 2062 vehicles per line, but the capacity of the highway using the speed-flow diagram, HCM2016, is equal to 2400 (veh/hr/ln) is on each passing line. The predicted capacity of the crossing in the created model is equal to 2190 vehicles per hour on the line, which is not much different from the time distance method. Also, the capacity obtained from Synchro and Aimsun software is 2034 and 2003, respectively, which is slightly different from the field measurement and the proposed model.

In this research, different methods were used to estimate the capacity of a road in normal traffic conditions. In order to suggest for future research, it can be suggested that special geographical conditions such as weather changes such as rainfall, and low light (night) can be investigated as the results of changes in road capacity.

On the other hand, in this research, different methods were used to estimate road capacity, which can be used in future research from other methods that were not used in this research.

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Research Paper

Optimization of Horizontal Road Alignment Based on Parameters Affecting its Cost and Lifespan Using Genetic Algorithm

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Abstract

This paper presents an approach for the optimization of horizontal road alignment with a focus on parameters affecting its cost and lifespan. The study area is the Bandar-e Anzali 16Km bypass highway, situated in north Iran, which holds significant economic, cultural, and environmental importance. The goal is to find the efficient and cost-effective alignment that adheres to design standards. The proposed methodology employs a multi-objective optimization technique using genetic algorithms in MATLAB. Various cost parameters, safety indicators, and environmental constraints are considered as decision variables to formulate the target performance. The genetic algorithm efficiently explores the design space, providing optimal solutions that fulfill all requirements and constraints. The output model ensures a balanced and practical approach to road design. The route design data was collected and the important variables affecting the route design were determined. Then, the optimal balance was evaluated using the genetic algorithms method. After analyzing the generated data, we propose the optimal horizontal alignment as the final recommended option, with four horizontal arcs and a length of 14.99km. The results demonstrate the effectiveness of the genetic algorithm-based method in achieving an optimal alignment for the Bandar-e Anzali bypass highway. The proposed solution reduces road construction costs and enhances safety while considering environmental impacts. This study highlights the importance of considering multiple parameters and utilizing advanced optimization techniques to achieve sustainable and cost-effective road designs. The proposed approach provides decision-makers with valuable tools to explore a wide range of design options and select the favorable alignment for construction.

Keywords: Road Geometric Design, Horizontal Alignment Optimization, Safety Considerations, Environmental Impact, Genetic Algorithm

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1. Introduction

Route design is a plan that is presented on the natural ground conditions in an area. The purpose of designing the connecting route between two points (origin point at the beginning and destination point at the end) is with the minimum possible cost as well as the maximum efficiency and usefulness. Of course, it is necessary to explain that in order to achieve an ideal plan in the proposed route plan, several limitations must be taken into account. The most important of these limitations can be classified as follows:

1) Design limitations based on standards and guidelines
2) Environmental restrictions in the intended area
3) Social restrictions on citizens and residents of the affected area

Achieving a horizontal alignment often may not lead to the best possible option, because there are countless proposed routes to connect two points of origin and destination, which will be based on the human judgment of design engineers. In this way, among the unlimited possible options between the origin and the destination, based on the judgment and intuition of the designers, a proposal is obtained as an output. In the meantime, many good options may have been overlooked. In order to examine all possible options on the one hand and to reduce the workload of design engineers, the study of automatic routing methods and methods that can achieve the best results with the lowest costs in the shortest time was started. Automatic methods significantly reduce road design problems, possible errors in manual design methods, and similar issues. In addition, automatic methods make it possible to use optimization techniques to search for the best path. Optimization techniques save design time and provide decision makers with powerful tools to search for the lowest cost option from a large number of possible options. Therefore, route optimization will result in significant savings in construction costs compared to methods that do not follow optimal road design. In recent years, many efforts have been made to realize the methods of determining the candidates of desirable roads. Today, new methods have been presented in developed countries based on new techniques. Some of these many methods that have been proposed in the last two decades are: change calculation method, network optimization, dynamic programming, numerical search, genetic algorithm and geographic information system.

In general, in road design, choosing the best option for a set of origin and destination components is very important. The concept of the best design candidate in this thesis is a way that the following parameters can be observed from three basic points of view according to the flowchart presented in Fig. 1. Considering all these parameters as well as the impact of each of the technical and economic parameters, it is a very difficult and time-consuming way. Traditional methods of determining optimal road options require errors due to large amount of data and time. Horizontal routing of a road is actually a view of the route that can be seen from the eyes of a bird in navigation between the origin and the desired destination. This step is made up of successive extensions that prepare the path at the meeting points with the help of circular horizontal arcs and connection curves (Clothoid). The connecting curves provide a more favorable driving experience with the help of its variable curvature along the track and its gradual change. The cost of road construction in the category of horizontal routing (route plan) depends on the cost of land acquisition and factors like that, so the main considerations in the horizontal design of the route is that the following should be avoided:

1) Lands that are purchased with It is limited or expensive.
2) Natural obstacles that involve more risk and engineering complications.
3) Lands that have high environmental importance.

In the optimization of the horizontal route, we intend to build a low-cost route by complying with the route design standards and reducing the subsequent environmental effects. However, what is important is that the path presented as a plan is useful and functional. Sometimes these two important goals may be in conflict with each other. In this study, the main road optimization model has been investigated as one of the most important classifications of communication arteries. In this model, it was tried to use different parameters to determine the appropriate candidate for road optimization. As mentioned in the previous section, these parameters can be divided into three main categories:

The first category: Cost parameters

A) Indirect cost: Road location cost and land cost.

B) Direct costd: structural cost and length-related cost.

The second category: Safety parameters

Legnth of straight paths, number of vertices of arcs (PI), radius of horizontal arcs and overlaps of horizontal arcs.

The third category: Constraint parameters

A) Dsign limitations: Checking the rights of way.

B) Environmental and geographical limitations: ecologically protected areas, air pollution cost and environmental conventions for greenhouse gas emissions.

Finally, using a genetic algorithm for optimization reduces the time and effort required to develop an optimal road design significantly. The genetic algorithm quickly and efficiently explores a large design space and identifies an optimal solution that meets all the design requirements and constraints and saves time and resources for road design professionals compared to traditional methods.

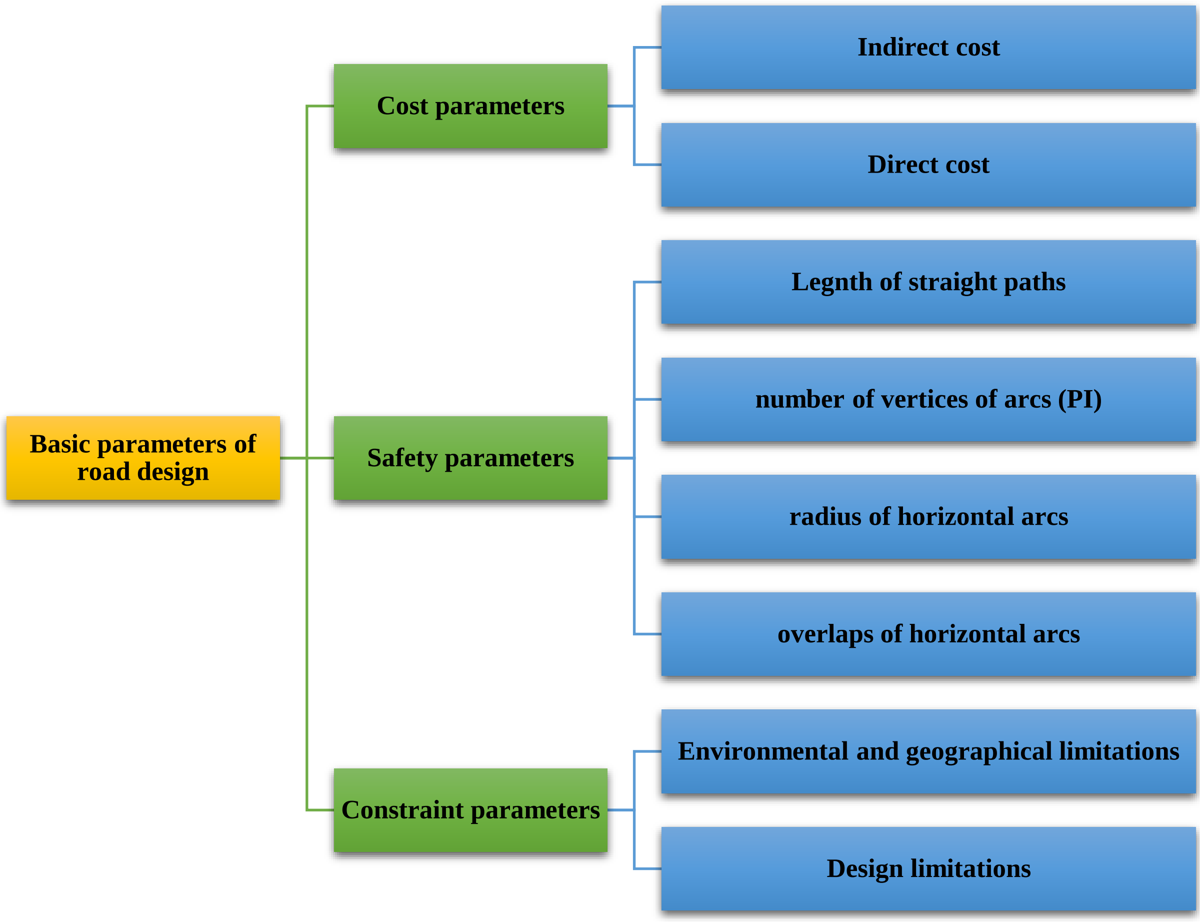

Figure 1. Flowchart of three basic parameters of road design

Although, Numerous inherent limitations exist in any research, often originating from factors beyond the researcher's influence. These constraints can impact the interpretation and generalization of research outcomes and may stem from various sources, such as methodological choices, data availability, or analysis techniques. Given that this study primarily concerns the practical application of a novel routing design approach, it deliberately maintains a delimited scope to enhance the clarity and decisiveness of its findings. The principal limitations encompass:

1) To indicate the horizontal alignment of the road, several intersection points (PI) are checked. The maximum number is set as N PIs according to the case study (Bandr-e Aanzali).

2) Among the cost components, only those that seem important to the optimal design approach are selected. Therefore, they have been formulated by approximation and simplification.

3) Route geometric design optimization in this research is limited to the horizontal alignment.

4) There are many variables beyond the researcher's control that can affect path optimization.

5) Statistical and design issues naturally exist in correlational studies.

6) There are limitations in data collection and statistical methods in all researches, including this research.

7) The genetic algorithm optimization model in this research is limited to selected cases.

8) The engineering data has been limited to the route and there are restrictions regarding vehicles and pedestrians.

2. Research Background

Optimization of road design using computers began in the 1960s and 1970s. Due to limited computational power, solving optimization problems accurately was difficult. The emergence of modern computers and GIS technology has given us the ability to solve the problem more accurately. The cost of road construction can be significantly minimized by solving mathematical models using modern computer programs. Many optimization models have been proposed to address this issue, each providing a solution from different perspectives. Although existing models work well in some aspects, they still have flaws that practically prevent their application.

The horizontal alignment of a road is composed of tangent sections connected to curved sections to smoothly change directions. Generally, circular curves are considered in the plan view to maintain centrifugal force and prevent lateral slip of the vehicle. This important feature can be achieved by creating appropriate curvature and cross slope based on design speed and lateral friction. The goal of optimizing the horizontal alignment of a road is to develop a mathematical search model to find the global or near-global optimal solution based on minimizing the total objective function cost within existing geometric design constraints.

The optimization problem of horizontal alignment of roads is more complex than the vertical alignment problem. [Jha et al, 2006] The main reasons are that horizontal alignment requires more data and its cost is dependent on vertical alignment, political, socio-economic, and environmental issues. In research, mainly three fundamental approaches have been studied: calculus of variations, network optimization, and dynamic programming.

The calculus of variations approach tries to find the curve connecting two endpoints in space that minimizes an integral function [Wan, 1995]. The nature of the road alignment optimization problem allows us to use the concept of calculus of variations to find the optimal alignment. In another study, the idea of calculus of variations was used to develop the principle of optimal curvature (OCP), which determines the optimal vertical and horizontal curvatures at each point [Howard, 1968]. To apply OCP, two numerical integration methods, namely the circular arc algorithm and the intrinsic equation method, were proposed [Shaw & Howard, 1981]. OCP was applied to determine the optimal alignment of a highway in South Florida [Shaw & Howard, 1982]. The two main requirements for using this method are that the cost function must be continuous and the cost function must be twice continuously differentiable. In practice, the cost function may not be continuous [Jha et al, 2006]. Although OCP ensures global optimization, it requires some assumptions that make it impractical.

In another research [Safarzadeh et al., 2006] they presented a model to find a corridor for the optimal alignment, which has access to all the main points and has the lowest total cost. The most important feature of this model is to consider areas that the route should not pass through for any reason. In this research, the evaluation of common routing methods has been done and finally, two mathematical models for routing in plain areas have been presented. In the first method, the impassable areas are not modeled, in the second method, the forbidden areas are modeled in the shape of a triangle, and the route is prevented from passing through these areas. One of the important issues of the route corridor plan is not to pass through the protected environmental or military areas. In the plains and Tepe rolling areas, passing through valleys, lakes, mountains or other such areas imposes a lot of cost on the project, so these areas, like the protected areas, are difficult areas for the corridor. The most important feature of the second method is to consider these areas in the optimal routing of the corridor. A very important point in the corridor plan is to determine the general model of the route, or in other words, the order of access to the points and the method of this access. Routing should be done with a comprehensive view and a long-term plan, so that the most cost-effective road network can be created. Therefore, one of the most important applications of the presented mathematical model is to use it to prepare a comprehensive plan for freeway and rail corridors in the country's plains and rolling hills. It can also be used for navigation on larger scale maps in plain areas. In this research, mathematical nonlinear programming model was used for modeling.

[Lee et al. 2009] proposed an exploratory method for optimizing the horizontal alignment, which works in two stages. In the first stage, it attempts to approximate a piecewise linear path, and in the second stage, it provides a solution to align the previously created piecewise linear path with an actual road alignment.

Kang and colleagues [Kang, 2012] provided an intelligent optimization tool that integrated genetic algorithms with a Geographic Information System (GIS) to optimize highway alignments. Two real highway projects in Maryland were analyzed using the model. The results show that the model can effectively optimize highway alignments in a complex area of various natural and cultural land use patterns. The model was able to significantly reduce the time required for planning and designing highways and produce cost-effective solutions.

Anouthet study proposed a bi-level optimization model that combined horizontal alignment, vertical alignment, and earthwork optimization to find an optimal alignment connecting two end-points in a specified corridor [Mondal et al., 2015]. The model used derivative-free optimization algorithms to solve the outer problem and gave an optimal horizontal alignment in the form of a linear-circular curve and an optimal vertical alignment in the form of a quadratic spline. The approach was tested on real-life data and improved the road alignment designed by civil engineers by 27% on average, resulting in potentially millions of dollars of savings.

The Path Planner Method (PPM), introduced by [Sushma and Maji, 2017], draws its foundation from the Rapidly-exploring-Random Tree (RRT) algorithm, a prominent tool in path planning. PPM is meticulously designed to efficiently explore complex high-dimensional spaces, with the primary aim of achieving an optimal horizontal highway alignment. The methodology revolves around generating random Points of Intersection (PIs) to comprehensively cover the entire study area. These PIs serve as the building blocks for a tree-like path that iteratively extends from the starting to the ending points. These paths adhere to prescribed geometric guidelines for highways while minimizing construction costs. The PPM operates through an interactive two-stage process. To evaluate its efficiency and applicability, a case study employs geographical mapping data from a location in Odisha, India. The results of this case study offer valuable insights into the PPM's effectiveness in optimizing horizontal highway alignment.

[Casal et al., 2017] present a comprehensive approach for optimizing horizontal road alignment, encompassing tangential segments, circular curves, and transition curves known as clothoids. Their model addresses a wide range of scenarios by capturing cost factors in a flexible line integral-based objective function. Practical applications are demonstrated through designing new road layouts and improving existing roads to meet current regulations, exemplified by the reconstruction of regional road NA-601 in northern Spain. This work provides a foundational reference for enhancing road alignment efficiency and compliance in road design and reconstruction.

In anouther research [Babapour et al., 2018], the focus was on the optimization of vertical alignment in road planning and construction, taking into account design constraints and costs. Various linear, nonlinear, and heuristic techniques were explored to minimize road construction costs by manipulating different variables. The utilization of genetic algorithms (GA) and Particle Swarm Optimization (PSO) was considered for efficient vertical alignment allocation. The study aimed to find a near-optimal forest road profile connecting specific endpoints, while considering design restrictions and cost evaluation. Parameters such as population size, crossing over, and mutation rate in GA, as well as best group and particle positions in PSO, were tested to achieve a global optimal solution. Comparative analysis of the optimization results using GA and PSO with the manual road profile drawing method revealed that both GA and PSO could effectively reduce earthwork volume costs and deliver smoother and better-aligned designs. Among the applied methods, GA demonstrated superiority in achieving optimal solutions with reduced computed costs, making it the most suitable approach for this problem. For larger numbers of control points, optimizing the fixed length of road profiles using GA yielded better results, while smoother outcomes were obtained for lower numbers of control points.

Anouther study, [Zhang et al. 2020] proposed a multi-objective optimization model for railway alignment design considering both economic and environmental objectives. The study aimed to find an economical and eco-friendly railway alignment that reduces negative impacts on mountain environments. The proposed method included two new quantitative indexes for measuring environmental impacts and a multi-objective optimization method based on the particle swarm optimization algorithm. The results showed that the proposed method effectively traded off economic and environmental objectives and provided a set of non-dominated alignment alternatives. This study provides a promising approach to the design of railway alignments in environmentally-sensitive regions.

Sushma and Maji (2020) introduced an innovative approach for optimizing the development of horizontal highway alignments in their next study. Horizontal alignment, a crucial aspect of road development, involves the interplay of three essential factors: the number of horizontal points of intersection (HPIs), their precise locations, and the corresponding horizontal curve radii. Determining these three factors simultaneously represents a significant challenge, particularly when undertaken manually. Most computer-aided methods currently available prioritize one or more of these factors within automated alignment development processes. However, these methods are not without limitations, including the approximation of HPI locations and the pre-selection of HPI numbers and curve radii. This study presents a novel motion-planning based algorithm designed to address these limitations and optimize the development of new horizontal alignments while considering both cost and environmental impacts. The algorithm simultaneously employs a low-discrepancy sampling technique to generate increasingly dense potential HPIs, enabling the rapid exploration of random trees to identify an appropriate number of intermediate HPIs at optimal locations. Furthermore, a sequential quadratic algorithm is employed to select curve radii that are optimally suited for the alignment. To enhance the practical applicability of this algorithm, it is integrated with a Geographic Information System (GIS) database. This integration facilitates the assessment of location-dependent costs and environmental impacts, ensuring that the alignment development process aligns with real-world conditions. The study utilized two real-world case study areas to compare results with those reported in existing literature and to evaluate the algorithm's backtracking capability. The results underscore the proficiency of the proposed algorithm in generating new alignments effectively.

[Biancardo et al. 2021] presented a result of study on the optimization of railway track alignment to connect growing inland mountainous areas. The study applied a multiobjective alignment optimization commonly used in highway projects to identify a better solution for constructing a high-speed railway track while considering technical and economic feasibilities. The study investigated two different and innovative scenarios: an unconventional ballastless superstructure and a reduced cross-section in a tunnel. The results showed that the ballastless superstructure had a better performance with a slight increase in cost. Both scenarios improved the preliminary alignment optimization, reducing the overall cost by 11% and 20%, respectively. This study demonstrates the potential of multiobjective alignment optimization in railway design, and the importance of considering innovative solutions that are more environment-friendly and cost-effective.

In the study by [Khalil et al. 2021], a method for optimizing the horizontal corridor of a highway in mountainous areas using GIS and critical failure state charts (CFSC) was proposed. The authors highlighted the importance of considering essential criteria related to construction, maintenance, and structural subjects during the preliminary design phase. To address the issue of road slope stability, soil properties were predicted using the California Bearing Ratio (CBR) test and CFSCs were proposed to evaluate the safe height of the slope and the need for supporting systems such as concrete retaining walls. The optimal location of the retaining walls was determined using GIS and Least-Cost Path Analysis (LCPA) method. A mathematical model was implemented to find the optimum corridor between two points, and the cost of the retaining wall was classified as low according to the adopted cost classification.

[Rouhi Mashhadsari and Behzadi, 2021] conducted a research study with the aim of reducing the number of accidents by investigating variables influencing the severity of injuries in accidents. This investigation involved the modification of the geometric design of road horizontal alignments. In this study, the researchers utilized three powerful machine learning techniques, including the Bayesian classifier, random forest, and support vector machine techniques. To begin, three prediction models for imbalanced data were created, revealing an inability to distinguish fatal data from injury data. To address this issue, three clustering techniques, including random clustering, k-means, and metaheuristic algorithms, were employed to balance the data. These metrics aided in the evaluation of the developed models, leading to the identification of the best-performing model. Ultimately, a sensitivity analysis was conducted on the best model, revealing that highways, horizontal curves, and oncoming variables play a significant role in accidents resulting in fatalities. Therefore, the modification and optimization of horizontal geometric design can significantly enhance route safety.

[Yu et al., 2022] introduced a multi-objective optimization framework targeting the design of horizontal highway alignment with considerations for safety and cost-efficiency. Their model exhibited notable achievements in terms of a reduced annual average accident rate and overall horizontal alignment length, concurrently ameliorating road safety and economic parameters. This model's potential applications extend to the development of dedicated road alignment optimization software or its integration into contemporary computer-aided design tools, which could subsequently mitigate debugging complexities and reduce the impact of subjective design decisions. Nevertheless, certain limitations became evident within this model, characterized by its somewhat oversimplified formulations of safety and economic objectives, rendering it particularly suitable for deployment during the design phase exclusively.

In a recent study by [Pu et al. 2023], a bi-objective model was proposed for railway alignment optimization that considered carbon emissions throughout the life cycle of a railway project. The model integrated carbon emissions generated during construction, operation, and maintenance stages, as well as the loss of carbon sink during a railway's life, into a single objective function. The model was solved using a particle swarm algorithm and successfully applied to a real-world railway case, demonstrating its effectiveness in minimizing both costs and carbon emissions. The study highlighted the importance of low-carbon design in railway alignment optimization, especially in the context of climate change.

Song et al. (2023) conducted an extensive literature review focusing on the optimization of alignment (AO) within the domains of roads, railways, and rail transit lines. Their investigation underscored the pivotal role of alignment determination in shaping the life-cycle performance of these transportation infrastructures. It was observed that manual alignment work is not only time-consuming but also labor-intensive. Consequently, the demand for intelligent AO methodologies has risen. Song and colleagues contributed the initial literature review within this sector spanning a quarter-century. Their study commenced with a comprehensive bibliometric visualization, unveiling the overarching characteristics of AO research. This review encompassed a scrutiny of prevailing mathematical models employed for formulating AO problems, incorporating applications grounded in Geographic Information Systems (GIS). Additionally, it delved into an extensive discussion concerning intelligent methodologies aimed at addressing the AO challenges. Two specific research areas were elucidated, embracing the concurrent optimization of railroad alignments and station locations, alongside the pertinent matter of existing alignment reconfiguration and redesign. In conclusion, the authors proffered a spectrum of twelve prospective research extensions and directions within this distinctive domain.

Zhang et al. (2023) presented an innovative approach in their next paper that introduces a Sequential Exploration Algorithm (SEA) designed to optimize horizontal road alignment in a distinct manner. Unlike conventional optimization methods, SEA systematically explores the entire optimization space in a sequential fashion, allowing for the independent adjustment of parameters for each node. This characteristic eliminates the need for rigid dependencies among performance indicators

(PIs), which is a common constraint in traditional optimization algorithms. SEA's versatility is further highlighted by its capacity to operate without preconceptions regarding the number or positioning of PIs. It excels in designing nearly optimal road alignments that adhere to geometric restrictions while also accounting for transition curves. A notable aspect of this algorithm is its direct optimization of geometric element parameters based on the actual milepost, eliminating the necessity for secondary optimization nesting during the process. The study conducted comparative analyses of the optimization outcomes using SEA, which included a problem of obstacle avoidance, a new road design scenario, and an existing road reconstruction problem. Results showed that the SEA outperforms two leading-edge optimization algorithms by yielding optimization improvements ranging from approximately 3% to 10%. This remarkable enhancement underscores the SEA's potential to significantly enhance optimization outcomes in horizontal road alignment design. Overall, this work offers a novel approach to road alignment optimization by effectively integrating discrete and continuous optimization components. The discrete element optimizes precision, while the continuous component addresses real optimization needs, providing a promising avenue for improving road design and reconstruction processes.

Previous studies have proposed various optimization models to address the issue of road alignment design from different perspectives, including calculus of variations, network optimization, and dynamic programming. However, in previous studies, the issue of optimizing the alignment in a simultaneous approach from both the perspective of modifying the geometric design of the route and the effects of incorrect route design on the environment has been less considered. In addition, most studies have mainly focused on the optimization of the geometric design, while the other variables such as environmetal and safety indicaors has been less considered. Moreover, the proposed models have not fully addressed the complexity of the problem, where environmental and socio-economic factors significantly influence the design. Therefore, there is a research gap in developing a comprehensive optimization model that considers horizontal alignment and takes into account environmental and socio-economic issues. The proposed models need to be more practical, adaptable, and capable of considering innovative solutions that are more environment-friendly and cost-effective.

3. Methodology

In this research, an optimization method for road design is presented, aiming to provide a set of horizontal alignment design options from a single stage of the design process. The study begins by identifying limitations and cost parameters, including technical, safety, and environmental factors affecting route design. It emphasizes the selection of crucial variables influencing the geometric design of horizontal roads. The research explores various optimization models to enhance optimization quality and formulates the final model considering cost, safety and limitation perspectives. The genetic algorithm method is employed to design the final optimization model. A key innovative aspect of this research lies in the consideration of safety aspects, including correcting horizontal arches and distances between arches, a crucial factor often overlooked in previous studies. Additionally, the study introduces the concept of optimizing the number of Points of Intersection (PIs) in road curves, directly related to design speed and road safety. The smaller the radius of curvature, the more PIs are needed for safety, highlighting the intricate relationship between curvature, safety, and design efficiency. Furthermore, the research pioneers the inclusion of pollution costs during the road's lifecycle, providing a holistic environmental perspective in road design. The study evaluates modifications to existing roads and incorporates environmental fees, a factor often disregarded in previous research, contributing significantly to the optimization process. The innovative model is applied to the Bandar Anzali Beltway, a critical area between the Caspian Sea and the Anzali Lagoon, demonstrating its potential in addressing complex real-world challenges.

The optimization model developed in this research serves as a groundbreaking tool for road design experts and engineers. It not only provides an automatic and scientifically sound method for optimizing road designs but also addresses critical safety aspects, environmental concerns, and user indirectional costs, which are often overlooked in traditional design methods. By employing genetic algorithms, the model efficiently explores vast design spaces, ensuring cost-effectiveness, safety, and efficiency in road networks. This approach stands as a pivotal step toward cost-effective, safe, and efficient road networks, aligning with the global efforts to enhance transportation infrastructure and minimize environmental impact.

This study aims to develop a comprehensive horizontal alignment optimization method that considers various parameters affecting the cost and lifespan of the road. this study proposes a multi-objective optimization approach that simultaneously minimizes the land acquisition cost, road construction cost, travel time cost and costs related to safety and the environment. The proposed method utilizes genetic algorithms to solve the multi-objective optimization problem, where performance indicators (PIs) are considered as decision variables for formulating the target performance. However, the cost function cannot be formulated as a function of PIs like in conventional multi-objective optimization problems, thus requiring a special multi-objective GA process. The PI coordinates are encoded in chromosomes, where the alleles of each chromosome represent continuous real numbers defined in the search space of the problem. The construction and user cost are evaluated for each path created by the coordinate information stored in the allele of the chromosomes. Based on the fitness function values, non-dominant and dominant solutions are classified, and separate selection pressures from non-dominant and dominant solutions are found based on total cost ranking. The next generation of chromosome sets is produced by crossover and mutation of the original solution set, leading to the reproduction of children and the achievement of optimal solutions. Overall, this proposed method provides a more practical, adaptable, and comprehensive approach to horizontal alignment optimization, considering various parameters and utilizing advanced optimization techniques.

An overview of the proposed method is shown in Fig. 2. In this flowchart, the following steps will be taken to provide the road optimization modeling process, with the goal of achieving horizontal alignment optimization.

4. Horizontal Path Variables and Objective Function

4.1. Design Variables

4.1.1. Geometric Variables

Horizontal alignment optimization plays a crucial role in road design to ensure efficient and safe vehicle operation within the available space while considering various constraints. This paper focuses on the significance of horizontal path constraint variables in genetic algorithm-based horizontal alignment optimization. These variables define the feasible design space and guide the search process towards high-quality solutions. Compulsory points, including start, end, and vertices, establish the path's endpoints and milestones, connecting the desired origin(O) and destination(D) points. The length of tangent lines and the angle of the apex of the arc affect the overall path length and curvature, influencing smoothness and vehicle stability. The center of the horizontal arc determines the curve's position relative to the road, affecting visibility and maneuverability. The intersection of the arc and tangent ensures a smooth transition between straight and curved sections. The arc's radius impacts lateral acceleration and ride comfort. Additionally, the total path length affects travel time, construction cost, and maintenance expenses. To optimize horizontal alignment, appropriate objective functions balancing design criteria and constraint variables are essential to generate practical, geometrically feasible solutions and achieve optimization goals effectively.

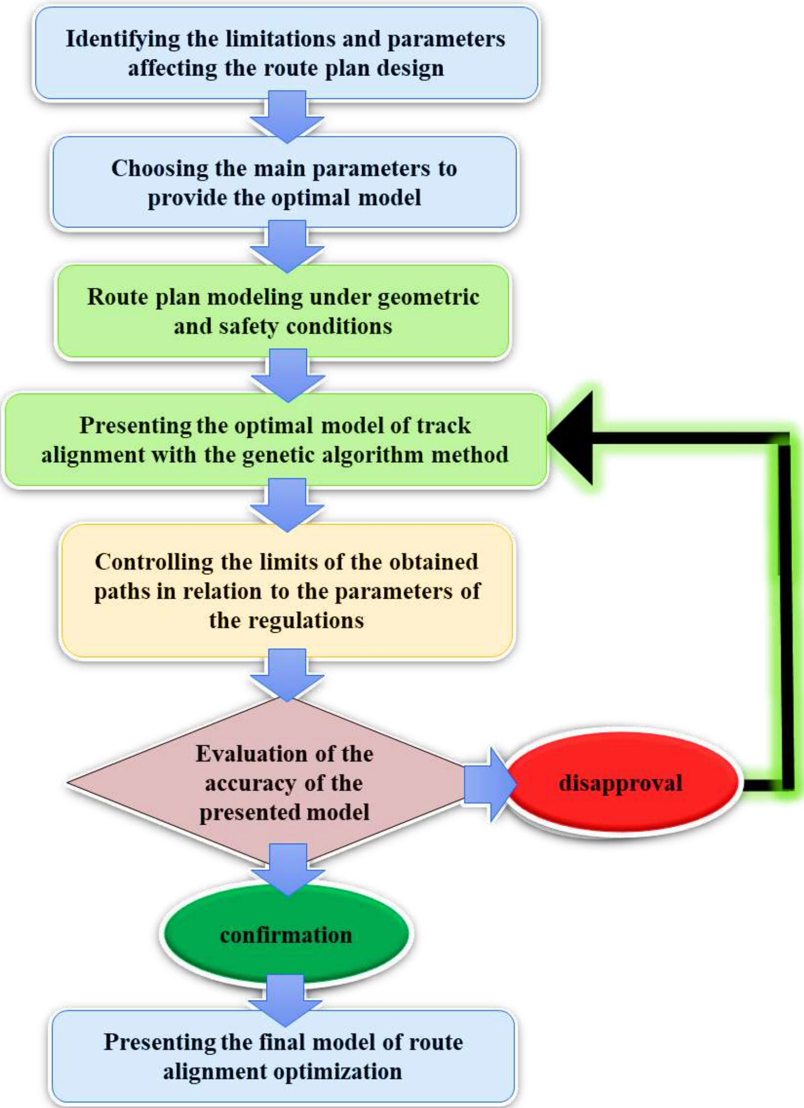

Figure 2. Flowchart of Research

n path design, the goal is to draw a path between two starting points O and ending D. The horizontal path that is planned should be a combination of straight sections (tangents), horizontal arcs and connecting arcs (Clothoid). (Fig. 3) If the proposed variant consists of N+1 tangent lines, we will have N vertices of the arc $v_i = (x_i . y_i)\ i = 1. \dots . N$, N simple circular arcs $R_i \geq 0. i = 1, \dots, N$ and N central angles of the arc $\Delta_i \geq 0. i = 1. \dots . N$ So for every N ∈ We will have N:

$$x^N = (x_1 . y_1 . R_1 . \Delta_1 . \dots . x_N . y_N . R_N . \Delta_N) \in R^{4N} \quad (1)$$

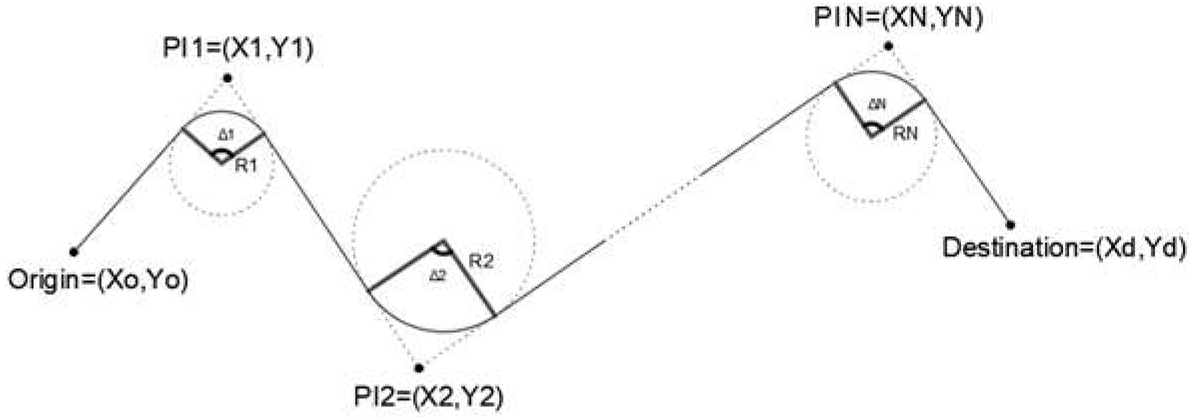

Figure 3. Horizontal path of communication between the starting point O and the end point D including the components of x^N vectors and the execution path C_{x^N}

Therefore, in road design, the vector of decision-making variables to solve the alignment optimization problem is x^N. In addition, the execution alignment of the road, which will also include arcs, is in the form of $C_{x^N} \subset R^2$, which is specified by x^N. (Fig. 4)

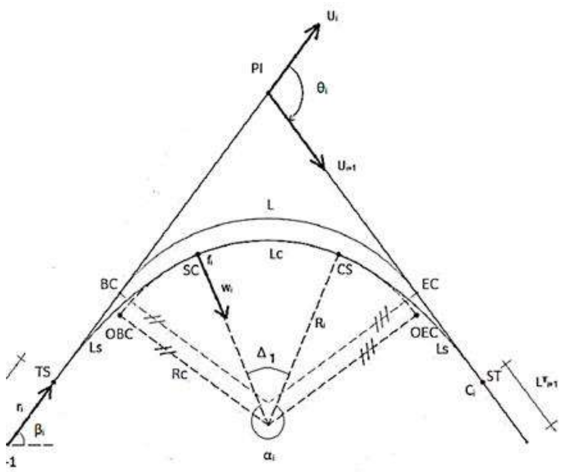

Figure 4. Contractual variables and vectors in the design of the horizontal alignment of the road

4.1.2. Safety Variables

Safety variables are of utmost importance in optimizing horizontal alignment as they directly impact the safety of road users. Factors like design speed, extreme height, and curvature radius significantly influence road safety. This paper explores the role of safety variables in genetic algorithm-based horizontal alignment optimization and their incorporation into objective functions and constraints to ensure safe and efficient solutions. Design speed, determined by safety levels, traffic volume, and roadside environment, can be maximized while meeting other objectives. The distance between consecutive horizontal arcs affects smoothness and continuity, and optimizing it considers driver visibility and stopping distance. Safety can be addressed using surrogate safety measures or direct integration of accident risk in the genetic algorithm through cost functions or constraints. Accident prediction models can estimate expected crash frequencies based on road geometry, allowing hybrid objective functions to combine safety considerations with construction cost and travel time. However, it is crucial to validate models and consider additional safety factors like traffic volume and driver behavior. A case study on Greater Tehran highways demonstrated the relationship between accidents and variables such as cross-section length and arc curvature. As a result, an accident occurrence variable with penalty imposition was incorporated into the path optimization objective function to enhance road safety.

4.1.3. Cost Variables

Environmental damage, air pollution, and the cost of land release are key cost variables that impact the optimization process using genetic algorithms. Firstly, environmental damage must be carefully considered during transportation infrastructure design, as road construction and operation can significantly affect wildlife habitats, water resources, and air quality. Genetic algorithms can be utilized to find design parameters that minimize the environmental impact of an alignment while meeting other objectives and constraints. Secondly, the optimization process should account for air pollution resulting from vehicle emissions, which can have adverse effects on public health and the environment. Genetic algorithms can identify design parameters that reduce vehicle emissions, optimize travel time, alleviate congestion, and enhance overall transport system efficiency. Lastly, the cost of land release is a crucial factor affecting route feasibility and cost-effectiveness. Genetic algorithms can identify design parameters that minimize land acquisition costs by optimizing the alignment to require less land or exploring alternative routes with reduced land acquisition needs. Overall, cost variables significantly influence horizontal path optimization using genetic algorithms and must be thoughtfully integrated into objective functions and constraints to ensure cost-effectiveness and environmental sustainability of the obtained solution.

4.2. Parametric Calculations of the Path Length

In the context of road alignment optimization, one critical aspect is the calculation of the path length. The path length refers to the distance traveled by a vehicle along the road, and it is influenced by several factors such as horizontal curvature, grade, and superelevation. Accurate parametric calculations of the path length are essential to determine the cost and lifespan of a road section accurately. In this study, we employ a genetic algorithm-based approach to optimize the horizontal road alignment based on parameters affecting its cost and lifespan, including the path length. By considering the path length as a critical parameter, we aim to develop an optimized road alignment that minimizes the overall construction and maintenance costs while ensuring a long lifespan for the road.

Considering that $C_{x^N} \subset R^2$ must be a combination of straight segments and circular curves connected by clothoids, the road alignment can be easily parametrized in terms of the arc length parameter. We assume that the alignment will start with a straight section $v_0 = c_0 = a$ and end $v_{N+1} = c_{N+1} = b$ in the same way. For i=0, 1, …, N and j=0, 1, ..., N+1 we will have:

- Run (the change in x from one to the other)

$$\Delta_x = x_j - x_{j-1} \quad (2)$$

- Rise (the change in y from one to the other)

$$\Delta_y = y_j - y_{j-1} \quad (3)$$

- The unit vector that gives the tangent direction of j

$$u_j(x^N) = \frac{1}{\|u_j\|} u_j \quad (4)$$

$$u_j = (\Delta_x . \Delta_y)$$

$$\|u_j\| = \sqrt{(\Delta_x)^2 + (\Delta_y)^2} \quad (5)$$

- Tangent azimuth j

$$\Delta_{x_j} = x_j - x_{j-1} \quad (6)$$

$$\emptyset_j(x^N) = \begin{cases} acos(\Delta_y) & if \Delta_{x_j} \geq 0 \\ 2\pi - acos(\Delta_y) & if \Delta_{x_j} < 0 \end{cases} \quad (7)$$

- Azimuth difference between tangents i and i+1

$$\theta_i(x^N) = |\emptyset_{i+1}(x^N) - \emptyset_i(x^N)| \quad (8)$$

- The length of the circular arc i

$$L_i^c(x^N) = R_i(\theta_i(x^N) - \Delta_i) \quad (9)$$

- Length of each circulating clothoid i

$$L_i^S(x^N) = R_i \Delta_i \quad (10)$$

- The distance between the straight segment i and the start of rotation i (the start of the arc’s clothoid) and thedistance between the end of rotation i (the end of the end of the arc) and the start of the straight segment i+1

$$C_i(x^N) = v_i - (\int_0^{L_i^C} cos\left(\frac{\tau^2}{2R_iL_i^S}\right) d\tau(x^N) + \left[\int_0^{L_i^C} sin\left(\frac{\tau^2}{2R_iL_i^S}\right) d\tau\right] tan\left(\frac{\theta_i - \Delta_i}{2}\right)(x^N) + \left[\frac{\int_0^{L_i^C} sin\left(\frac{\tau^2}{2R_iL_i^S}\right) d\tau}{cos\left(\frac{\theta_i - \Delta_i}{2}\right)}\right. + R_i\left|\left(\frac{sin\left(\frac{\Delta_i}{2}\right)}{sin\left(\frac{\pi - \Delta_i}{2}\right)}\right)(x^N)\, u_i(x^N) \quad (11)$$

- The length of the straight section j (the distance of the direction from the end of the p.c j-1 to the start of j) where r j is a vector that starts at point C j-1 and ends at point t j

$$L_i^T(x^N) = r_j(x^N) \cdot u_i(x^N) \quad (12)$$

Considering $C_{x^N} \subset R^2$the following conditions must always be met:

1- The radii and central angles of simple circular arcs must be positive (non-negative).

$$R_i \geq 0;\ \Delta_i \geq 0;\ i = 0.1. \dots . N \quad (13)$$

2- The angles of simple circular arcs must be smaller than the difference in azimuths between the tangents on the sides of each turn.

$$\theta_i(x^N) - \Delta_i \geq 0;\ i = 0.1. \dots . N \quad (14)$$

Turn i+1 must start after the end of turn i.

$$L_j^T(x^N) \geq 0;\ i = 0.1. \dots . N + 1 \quad (15)$$

With these explanations, the total length of the road is:

$$L_j(x^N) = L_1^T(x^N) + \sum_{k=1}^{j-1} 2L_k^S(x^N) + L_k^C(x^N) + L_{k+1}^T(x^N) \quad (16)$$

Despite meeting numerous above conditions, not all routes can be deemed acceptable for road design. Legal restrictions imposed by the laws of each country can significantly influence design elements. Constraints, such as limits on culvert lengths, restrictions on straight sections, prescribed distances between consecutive curves, and others, play a crucial role in determining the feasibility of a road alignment. Additionally, certain areas may be designated as unsuitable for the passage of the horizontal alignment, while others may be recommended for inclusion. Therefore, it is essential to address these constraints during the optimization process to ensure a well-designed and compliant road alignment.

4.3. Route Optimization Formulation

Generaly, all these limits that we mentioned above can be collected in a series Cad where: $C \subset R^2$. The Cad series depends on the specific problem we are dealing with. C is also an acceptable cutoff for the new way. Therefore, we define the series as follows:

$$X_{ad}^N = \left\{ \begin{matrix} X^N \in R^{4N} \\ Conditions: 13 - 15\ \&\ C_{x^N} \in C_{ad} \end{matrix} \right\} \quad (17)$$

On the contrary, the primary objective of designing a road alignment is to optimize specific technical aspects, which include minimizing various factors such as road length, earthmoving operations, land acquisition and clearance costs, and environmental impacts, among others. The definition and calculation of the objective function for each practical application hold significant importance. To facilitate the search for a straightforward and universally applicable formula for this problem, we introduce the cost function as follows:

$$\begin{matrix} F: C_{ad} \to R\ \ \&\ \ CF^N: R^{4N} \to R \\ CF^N(x^N) = F(C_{x^N}) \end{matrix} \quad (18)$$

The problem of achieving the optimal design for the horizontal alignment that connects the initial point "O" and the final point "D" involves finding a solution where the cost function C_{x^N} attains its minimum value. The objective is to determine the most efficient alignment configuration that minimizes the overall cost associated with the road construction while ensuring a safe and reliable connection between the specified points.

$$\min_{x^N \in X_{ad}^N} CF^N(x^N) \quad (19)$$

The mathematical function F, represented by the series X_{ad}^N, is well-defined for any specific problem. However, obtaining an effective expression of the function F that comprehensively accounts for all associated costs can be challenging in numerous practical applications. For instance, considering the cost of earthworks based on the vertical alignment design can pose difficulties. In this article, the cost associated with each point in the domain is denoted by a function P(X,Y). Consequently, by summing the costs of all locations along the route, we arrive at the total cost of the project, expressed as below. In addition, the parametric expression C_{x^N} in the execution path including arcs, the objective function J^N is defined as follows:

$$F(C) = \int_C p(x.y)\, d\sigma \tag{20}$$

$$CF^N(x^N) = \int_0^{L(x^N)} p(\sigma_{x^N}(s))\, ds \tag{21}$$

The concept of price, denoted by the function P serves as a versatile model encompassing a wide array of possibilities, including economic factors (such as land release costs, asphalt expenses, and earthworks), environmental and ecological considerations, as well as political aspects. This cost function can also be utilized as a penalty mechanism for certain points, thereby simplifying the Cad set by incorporating regions where the design should not be included in the objective function. Additionally, P(X,Y) can be formulated as a weighted sum, representing a combination of various price components.

Obtaining a P-function, akin to an F-function, can be a complex task when attempting to encompass all potential costs. However, in certain straightforward applications, defining the P-function may prove relatively straightforward. In this article, we provide an illustrative example of optimizing an alignment, where the P-function is easily defined, showcasing its practical applicability.

The consideration of the price function P as a versatile model that encompasses a wide range of possibilities, including economic, environmental, ecological, and political factors, plays a crucial role in the optimization of horizontal road alignment. By incorporating the cost function, the design process can effectively address various constraints and penalties associated with specific points, ultimately leading to a more efficient and feasible road alignment.

While obtaining a comprehensive P-function may pose challenges in applications involving numerous costs, simpler cases, like the one presented in this article, demonstrate the ease with which the P-function can be defined and utilized for alignment optimization.

Overall, the integration of the cost function P and its role in the optimization process highlight the significance of considering multiple parameters to achieve an optimal road design that balances economic efficiency, environmental sustainability, and safety. This approach ensures the successful implementation of road projects that meet both engineering standards and regulatory requirements, paving the way for more effective and sustainable transportation infrastructure.

4.4. Objective Function

Route optimization aims to achieve a dual objective, encompassing the reduction of both construction costs and overall route expenses during lifespan. From the perspective of road users, the ideal route design should entail minimal costs in terms of travel-time expenditure, vehicle operation, and accident-related expenses. Conversely, the governmental authorities seek to establish a path with the lowest toll charges, construction costs (including paving), and maintenance expenditures. However, it is often challenging to find a proposed route that can fully optimize both of these objectives simultaneously. In such instances, the designer aims to provide a set of optimized routes, each representing different trade-offs between the aforementioned objectives. As a result, both construction costs and route expenses need to be minimized concurrently, giving rise to the following mathematical formulation:

$$\min f(PI_1, PI_2, \ldots, PI_n) \quad (22)$$

The PI variables are integral components of the problem's objective function, as they play a crucial role in determining the optimal path. Consequently, these PI variables directly impact the various costs associated with the route. Hence, the costs are considered as indirect functions of the path PIs. This distinctive relationship between the PI variables and costs renders the challenge of multiple path optimization a unique and intriguing problem within the domain of multiple optimization.

The genetic algorithm possesses a remarkable capability to handle multi-dimensional and multi-objective optimization problems. In the context of multi-dimensional optimization, this algorithm effectively conducts a simultaneous search across multiple variables' solution space. Similarly, in multi-objective optimization scenarios, the genetic algorithm adeptly identifies multiple optimal solutions within the solution space. In light of these advantages, this paper utilizes the genetic algorithm to address the problem at hand. The approach involves creating an initial variant between the specified starting and ending points, and subsequently designing the corresponding arcs, while adhering to defined arc vertex points and constraints. The optimization process then focuses on reducing project costs while taking into account paramount factors such as safety and environmental considerations.

This research utilized MATLAB to implement a genetic algorithm aimed at optimizing design parameters while adhering to specific design constraints. The genetic algorithm employed a population of candidate solutions, which underwent evaluation based on their fitness, i.e., how well they satisfied the design requirements. By employing selection, crossover, and mutation operators, the genetic algorithm generated a new population of candidate solutions, iteratively refining them over successive generations. Each candidate solution is represented using a coding scheme based on coordinates derived from Important Points (PIs), which encompass both the start and end points, as well as other relevant points along the path. The genes present in the chromosomal structure encode the decision variables, forming the basis for the optimization process.

Moreover, a multiple random point crossover technique is utilized to exchange a segment or segments of genes between two individuals, resulting in the formation of two offspring. During this process, the entire gene code, consisting of X and Y coordinates, within the identified segments is swapped between the parent individuals.

In this paper, the costs mentioned above are combined linearly to formulate the total cost (C_{Total}), and the objective of the process is to minimize C_{Total}:

$$\min(C_{Total} = \sum_{i=1}^{n} C_i) \quad (23)$$

Where C_i represent each individual cost component such as geometric, safety and other costs that mentioned above. Different combinations of the fitness function could also be considered for the optimization process.

5. Study Area

The objective of this study is to determine the optimal horizontal alignment between two origin and destination points, taking into account environmental considerations, cost parameters, and safety indicators. The study area is the Bandar-e Anzali bypass highway, a 16-kilometer-long highway located on the southern side of the city and between the Caspian Sea and the Anzali International Wetland in Guilan province, Iran. This region is of high importance due to its economic, tourism, political, military, and cultural significance. (Fig. 5)

The Bandar-e Anzali bypass highway is part of the 700-kilometer-long Astara-Gorgan highway, which is considered an important transportation axis in Iran. Despite the fact that the construction of this highway started in 1998, it is still only 50% physically advanced.

Therefore, the study and review of the existing 16-kilometer route of the highway will be effective in evaluating the current situation and improving the remaining parts.

A portion of the 16-kilometer route of the highway passes through the connection point of the Anzali International Wetland to the Caspian Sea. Failure to follow environmental considerations along the way can have destructive effects on this delta, including increasing erosion of the wetland's watershed, changing the use of its marginal lands, heavy vehicle traffic, noise pollution, and air pollution caused by passing traffic. Anzali International Wetland is a biosphere reserve and one of the most valuable aquatic and coastal ecosystems in Iran, which is registered in the list of wetlands with severe ecological changes in the "Montreux" list of the Ramsar International Convention. This wetland has the ability to attract tourists, wetland plants as a natural refinery, and fresh water storage resources for irrigation and agriculture. Additionally, it is the habitat of some migratory birds, the spawning place of all kinds of aquatic animals, and the factor of attracting floods and preventing flooding of the urban area.

To determine the optimal horizontal alignment of the highway, road design data was collected from consulting engineers (Table 1). Then, important variables affecting the route design were determined, and the optimality of the route was evaluated using the genetic algorithm model. After studying and checking the generated information, the optimal route was presented as the final proposed option. This optimized route is considered the shortest and most economically suitable path between the two points in the study area on the edge of Anzali Lagoon, with the least consequences and biological hazards for the region.

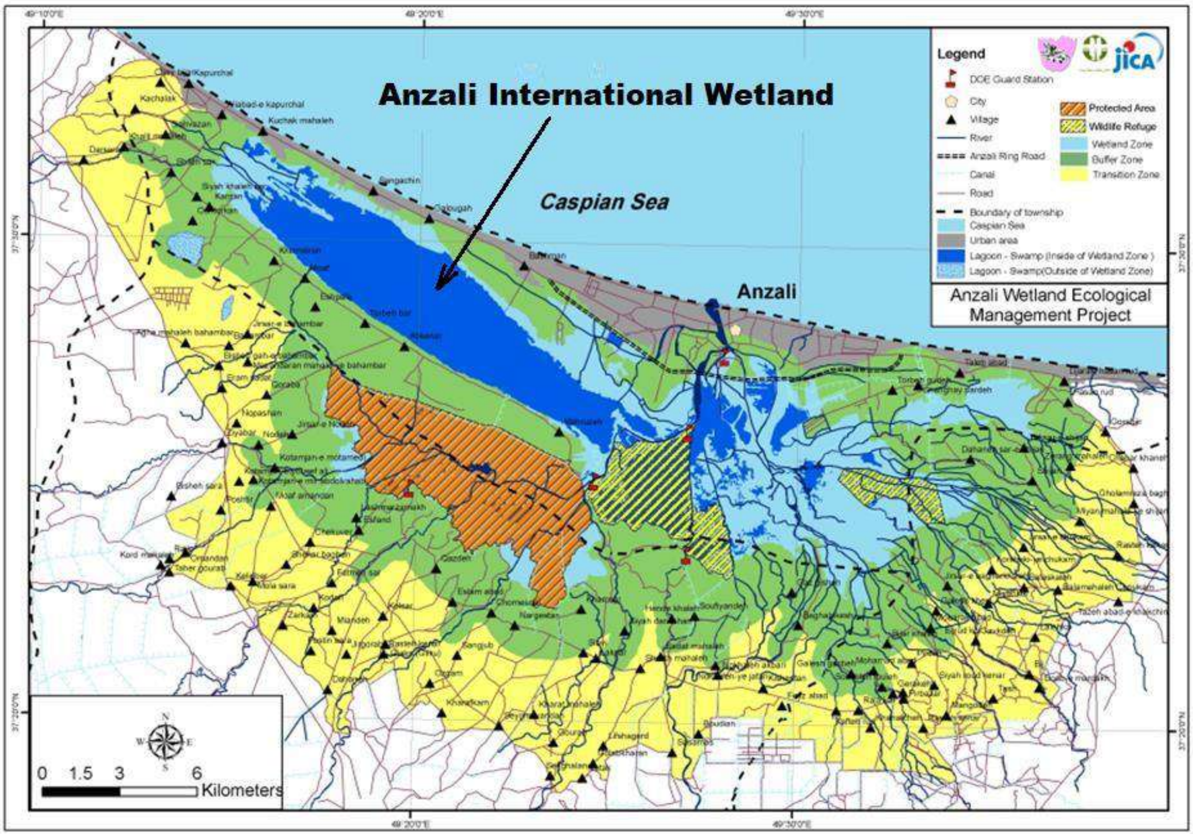

Figure 5. Study area zone: Bandar Anzali international wetland environment

Table 1. Data collected from the study area

Number of PIs	$PI_i = (x_i . y_i)$	R_i	Δ_i	Curve Lenght	Tangent Lenght
Start Point	000.00,3801.73	-	-	-	-
					429.74
PI 1	397.79,3359.20	1500	12.58	329.26	
					4814.49
PI 2	4651.96,327.99	700	38.41	469.28	
					311.12
PI 3	5558.61,374.55	3000	13.42	702.54	
					1466.92
PI 4	7583.90,000.00	2000	13.68	477.39	
					1110.90
PI 5	9105.70,085.04	2000	9.02	346.16	
					224.61
PI 6	9701.11,024.39	1000	22.67	395.64	
					1060.27
PI 7	11058.77,435.63	1000	17.94	313.15	
					1655.77
PI 8	13236.97,394.17	700	55.07	672.82	
					380.74
End Point	13675.48,997.30	-	-	-	-

Other Properties	
Design Speed	110 Kmph
Total Curvatre	25%
Total Tangent	75%
Road Boundary	38 m
Highwy Class	Median Divided
Environment	Int. Wetland
Lane NO.	2 / Line
Physical Situaion	51%
Longitudinal Sploe	±1%
Topography	Flat

6. Discussions and Results

In this section, we present the methodology for optimizing the horizontal alignment of an existing road using the genetic algorithm. The objective is to upgrade the old road, which has been under construction for a long time, and align it with current design rules, such as the use of connecting arches, maximum radius restrictions in arcs, and length of straight segments. Our goal is to design a new horizontal alignment connecting points O and D while making use of the old design and adhering to legal restrictions. For this purpose, we assume that the old plot of the graph of a function is known:

$$y_{old}:\ [x_{in}, x_{end}]\ \subset R \to R. \quad O = (x_{in}, y_{old}(x_{in})) \quad D = (x_{end}, y_{old}(x_{end})) \tag{24}$$

The first step is to compile the Cad series with all the constraints that the new design must meet and determine X_{ad}^{N}. This step is problem-specific and will be further elaborated on in the case study of the Bandar-e Anzali bypass presented in the next section.

Next, we define an objective function that evaluates the quality of each alignment. If our goal is to make use of the existing road as much as possible, we assign a price to each point based on its distance y from the old road. Points that lie on the old road are assigned a price of zero (0), while points whose distance y exceeds a certain maximum range dmax are assigned a price of one (1). For other points, we use a monotonically increasing function of the distance y as the price. The cost function P(X,Y) is akin to a valley along the old road. If the new design deviates from the old route (y>dmax), we charge an equal cost for each new section built while aiming to minimize the length of the horizontal alignment (Fig. 6).

$$p(x.y) = p_{y_{old(x)}}(y) \quad . \quad y_0 \in R \tag{25}$$

$$\Delta_y = y - y_0 \tag{26}$$

$$a = \left(\frac{\sqrt{2}}{d_{max}}\right)^2, b = \left(\frac{1}{d_{max}}\right)^4 \tag{27}$$

$$p_{y0}(y) = \begin{cases} a\Delta_y^2 - b\Delta_y^4 & if\ y < y_0 \pm d_{max} \\ 1 & if\ y \geq if\ y < y_0 \pm d_{max} \end{cases} \quad (28)$$

We apply this method to optimize a section of the Bandar-e Anzali bypass highway, which was previously designed in the 1970s as a two-way road with a crossing lane on each side. Later, it was revised in the mid-1990s and converted into a median divided highway in 2007 due to increased traffic needs. However, despite the passage of over 23 years since the start of construction, half of the project remains incomplete. Therefore, we aim to optimize the alignment to update it from its initial design while considering the impact on the environment around the track. The plan of the Bandar-e Anzali bypass variant based on the contractual coordinates of this article and its satellite map are shown in Fig. 7.

Figure 6 shows the environmental constraints around the route that need to be considered during optimization. The Bandar-e Anzali bypass road boundary is 38 meters on both sides of the axis, and an additional 100 meters is considered as the construction boundary on the southern side. The national railway boundary is approximately 100 m from the vicinity of the road boundary in the northern part of the route, which is considered the limit of the northern development. We assume a corridor of 138 meters on both sides of the road (2dmax) as the width of the optimization area.

In order to apply our methodology to this particular case, we perform the following steps:

Step 1: We determine the allowed set of X^N according to the restrictions that the new plan must provide. In this paper, we assume that the radius of all circular curves should be at least 300 meters, the length of clotuids should be between 80 and 450 meters, the length of each circular arc should be between 85 and 1300 meters, and the straight segments should be between 100 and 2500 meters.

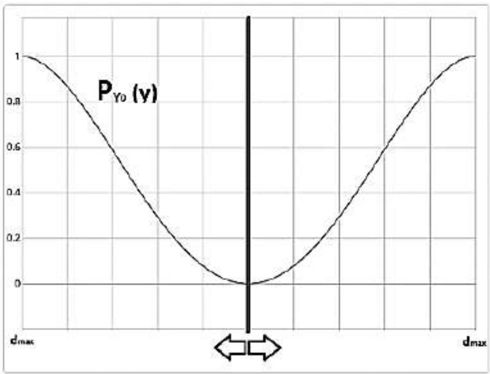

Figure 6. Cost Function

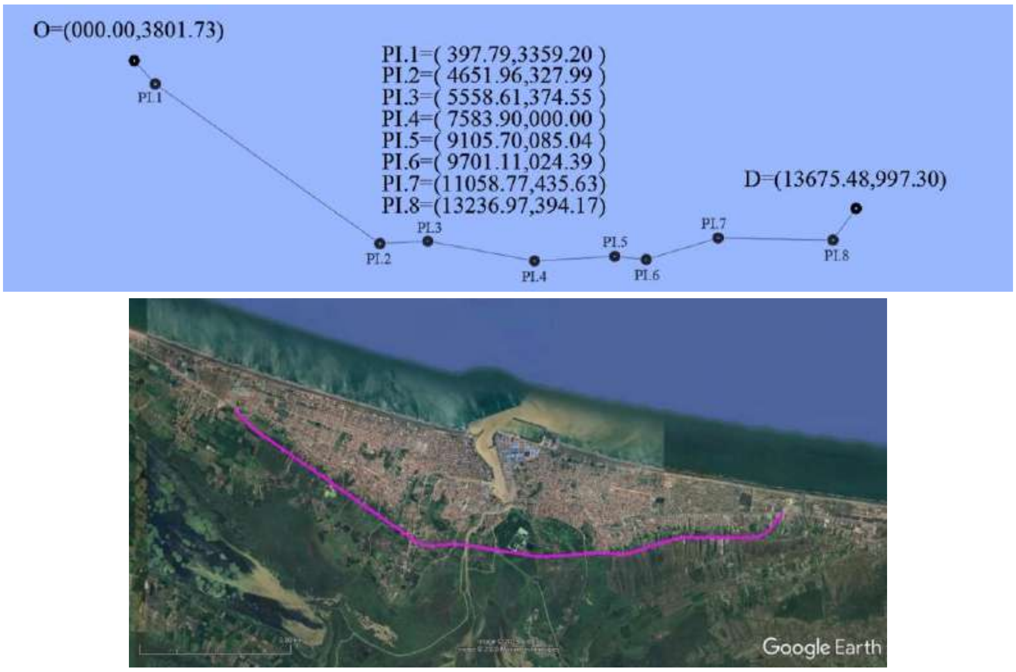

Figure 7. Anzali bypass based on the contractual coordinates of this article and its satellite map

To apply our methodology to this specific case, we undertake the following steps:

Step 1: We establish the permissible set of X^N based on the constraints imposed by the new plan. For this study, we assume that the radius of all circular curves must be no less than 300 meters, the length of clothoids should range from 80 to 450 meters, the length of each circular arc should fall between 85 and 1300 meters, and the straight segments should be within the range of 100 to 2500 meters.

According to Regulation No. 161 of the Plan and Budget Organization (Journal of Geometric Design of Roads), certain restrictions must be taken into account. For a design speed of 110 km/h, the minimum radius of horizontal arcs should range from 415 to 635 meters (depending on the elevation and friction coefficient). However, given that the radius of the existing arches of the Bandar-e Anzali bypass exceeds 700 meters, we set the minimum radius at 700 meters, which is slightly greater than the 635 meters stipulated by the aforementioned regulation.

In terms of the bend length, a radius limit of 150 to 1000 meters has been proposed for two-lane roads, while no limit has been established for four-lane roads. Additionally, arcs with a radius greater than 6000 meters can be designed as a parabola. Hence, we aim to set the radius of circular arcs up to 6000 meters. The minimum radius of the arc that requires a clothoid arc to ensure safety and ease of driving is 1000 meters and 1700 meters at design speeds of 80 km/h and 100 km/h, respectively. Consequently, by interpolation, this radius value for a speed of 110 km/h is equivalent to 2050 meters, which we round down to 2000 meters for ease of design. The minimum length of the clothoid is also taken into account, and we consider it as 200 meters for a speed of 40 km/h.

The TRB1195 regulation recommends the minimum and maximum length of the tangent between two arcs, with the minimum being proportional to the functional speed of traffic flow and the maximum related to driver fatigue, estimated to be roughly between 6 and 20 times the design speed of the route. However, AASHTO does not provide a specific value for this parameter. For a design speed of 110 km/h, the minimum distance between two turns in the same direction should be 600 meters, which corresponds to 660 to 2200 meters for a design speed of 110 km/h. Additionally, a maximum of 3000 meters is suggested to mitigate the risk of driver fatigue. Therefore, for the sake of simplicity and ease of design, we can consider the minimum and maximum values to be between 600 meters and 2500 meters.

Therefore, the outputs will be evaluated with the limits. At the same time, there is no limit for other beginning and ending parts outside of it.

Step 2: From the coordinates of a number of points of the old route and its execution maps, we will have the function of the old route. In some cases, it is possible to use the interpolation of points to obtain a cubic spline.

Step 3: We consider the value of d_{max}=0.1km from the old $\mathbf{y_{old}}$ route made in step 2. Based on formula 25, we present the cost function p(X,Y) and based on formula 21, J^N.

Step 4: Based on the acceptable series X_{ad}^N in step 1 and the CF^N function in step 3, for each N=0, 1,..., solve problem by using programming in the MATLAB environment and using the genetic optimization algorithm we show.

To ensure that the problem is solved correctly, it is crucial to adhere to a set of constraints. Failure to do so can lead to false solutions. Several important constraints can help to expedite the problem-solving process and guide the solution towards optimality. These include: (1) defining the interval for the start and end of the proposed routes, (2) defining the corridor width with a maximum value of 2dmax, and (3) restricting the number of PIs for the new alternative route to the existing axis.

As indicated in Table 2, the optimal option for improving the alignment is the one with four turns (N = 4). The corresponding optimal designs are illustrated in Fig. 8-a. An examination of the figure and the data reveals that an increase in the number of turns results in a better fit with the old design. When N = 1, and only one turn is permitted, the optimal solution is located at the intersection of the longest straight segment of the old route. Moreover, it should be noted that the first proposed alignment led to greater infiltration in the wetland bed (to the south).

Finally, in Fig. 8-b, we compare the current road improvement with our proposed solution for N = 4. The results show that both designs are in close proximity to each other. This finding is significant and suggests that the proposed method can be an effective approach for addressing road modification in the road reconstruction projects presented in this section.

8-a) All suggested variants

8-b) Suggested alignment by N=4 PIs

Figure 8. Output alignments of Optimization

7. Conclusions

Designing a road is a multifaceted and challenging undertaking. The increasing concern for safety, environmental impact, and irreparable costs resulting from improper road design necessitates a flexible, dynamic, and sustainable framework for improving road and environmental indicators. Traditional design methods and decision-making models based solely on human expertise and intuition are inadequate for maintaining safety, environmental compatibility, and comprehensive optimization. Therefore, there is a need for an algorithm that can provide optimal road alignment based on full parameterization, interpretation of costs, and the ability to address various problems while reducing potential environmental and safety risks.

In this study, we proposed a genetic algorithm-based optimization method to obtain the optimal alignment design for the Bandar-e Anzali bypass highway. The results confirm the effectiveness of the proposed method in achieving the optimal alignment, thereby reducing road costs and increasing safety. The obtained results also support the potential of this method to improve the quality of road improvement in road reconstruction projects, particularly in areas of high environmental importance. Furthermore, the proposed method can be extended to the design of the vertical alignment of roads or both horizontal and vertical alignments.

However, optimizing complex objective functions that include technical road specifications as well as environmental impacts can be challenging. Hence, the genetic algorithm optimization technique can be an effective solution for addressing these problems. In conclusion, this study has demonstrated the potential of genetic algorithm-based optimization for the design of horizontal road alignment, and further research can be conducted to explore the application of three-dimensional techniques for optimizing both horizontal and vertical alignments.

Table 2. Numerical results obtained to solve the problem

	Number of PIs	$v_i = (x_i . y_i)$	R_i	Δ_i	Curvature Percentage	Tangent Percentage	L_{Total}	CF
i = 1	1	5769.45, -393.67	5.02	0.80	27%	73%	14.93	7.12
i = 2	2	5026.62,176.74	4.70	0.59	32%	68%	14.91	4.10
		10518.48, -024.76	5.79	0.35				
i = 3	3	4271.75, 470.96	1.92	0.52	20%	80%	14.96	2.09
		7583.90,000.00	2.86	0.20				
		11357.42, 210.52	5.29	0.27				
i = 4	4	4241.77,508.27	1.87	0.51	14%	86%	14.99	1.03
		7369.23,032.65	2.23	0.15				
		9701.11,024.39	3.56	0.13				
		12608.95,406.13	0.95	0.38				
i = 5	5	397.79, 3359.20	0.83	0.22	26%	74%	15.00	2.53
		4651.96,327.99	3.18	0.51				
		7583.90,000.00	2.96	0.24				
		11058.77,435.63	5.44	0.14				
		13236.97,394.17	0.70	0.96				
i = 6	6	397.79, 3359.20	0.80	0.22	17%	83%	15.15	1.98
		4651.96,327.99	1.25	0.51				
		7583.90,000.00	3.27	0.12				
		9701.11,024.39	0.85	0.28				
		11058.77,435.63	1.13	0.31				
		13236.97,394.17	0.75	0.96				

	Number of PIs	$v_i = (x_i . y_i)$	R_i	Δ_i	Curvature Percentage	Tangent Percentage	L Total	CF
i = 7	7	397.79, 3359.20	0.70	0.22	27%	73%	15.16	1.53
		4651.96,327.99	0.70	0.67				
		5558.61,374.55	3.04	0.23				
		7583.90,000.00	3.16	0.19				
		9701.11,024.39	3.87	0.28				
		11058.77,435.63	1.21	0.31				
		13236.97,394.17	0.70	0.96				

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Research Paper

Evaluation of the Effect of Cellulose Base Mixture on the Behavior of Rheology and Performance of Bitumen

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Abstract

Bitumen and asphalt mixture, cellulose fibers have attracted more attention of researchers due to their lower price and availability; the purpose of this research is to investigate the possibility of using cheap waste materials from paper factories to replace expensive modifiers, which can increase the life of asphalt pavement and reduce the need for its frequent repairs . In this research, the physical properties of the bitumen modified with cellulose fibers and black liquor have been investigated. The results showed that the increase in stiffness of the bitumen containing cellulose micro fibers and liquor. The increase in bitumen stiffness has decreased the degree of penetration and increased the softening point in the modified bitumen. The viscosity of the modified bitumen also increased with increasing stiffness. The results also showed the improvement of the high-temperature performance of all the samples modified with cellulose micro fibers and liquor. However, the improvement of the low temperature of the modified bitumen is limited to the use of 4 to 6% cellulose microfibers. Increasing the resistance to rutting of the modified bitumen showed the positive effect of using cellulose micro-fibers in order to modify the properties of the base bitumen; Therefore, by using the wastes of paper factories, it is possible to achieve favorable results in reducing the common failures of asphalt pavements, including rutting at high temperature and cracking at low temperature, and reducing the costs of modifying bitumen and asphalt mixtures.

Keywords: cellulose fibers, black liquor, rheological properties, dynamic shear rheometer test, bending beam rheometer test

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1. Introduction

As one of the most widely used human and goods transportation infrastructures around the world, roads play an essential role in the economic development of any region (Banerjee et al., 2020). Today, the good quality of road construction and implementation can play an effective role in reducing travel time, vehicle maintenance costs, and also road repair and maintenance costs (Small et al., 2012).

At present, asphalt pavements constitute a significant part of road pavements. This type of pavement consists of a combination of aggregates and bitumen. Despite the share of 4 to 7% of bitumen in the asphalt mixture, this substance plays an essential role in the physical and chemical properties of the asphalt mixture as well as its durability and stability. Therefore, the quality of asphalt pavement depends on the used bitumen and the use of appropriate bitumen can have a significant effect on the resistance and reduction of asphalt pavement damages such as cracking, rutting and etc. For this, a lot of research has been done to improve the properties of bitumen in order to reduce the destructive effect of atmospheric factors and also the effect of successive loadings caused by the traffic of vehicles on asphalt pavements (Mashaan et al., 2021).

The purpose of adding fibers to bitumen is to increase the tensile strength of bitumen and, as a result, to increase the ability of bitumen to absorb strain energy during the fatigue and failure process. This action makes the bitumen able to withstand more tensile forces and, as a result, show better performance in the face of fatigue and failure conditions (Mahrez et al., 2003).

Both natural and synthetic fibers have been used in the research conducted to modify asphalt mixtures. The use of fibers in granular mastic asphalt strengthens and hardens the asphalt mixture, and chemical reaction does not occur by adding the fibers. Among the advantages of using fibers in asphalt pavement, we can mention the reduction of fatigue and thermal cracks, reduction of reflective cracks and economic benefits due to the increase of the useful life of asphalt pavement modified with fibers (Mahrez & Karim, 2007).

In a study, Wu and his colleagues (2007) studied the asphalt mixtures modified with three types of cellulose, polyester and mineral fibers (with values of 0.3%, 0.3% and 0.4%, respectively) by dynamic modulus test. By examining the dynamic modulus test results of the asphalt including the dynamic modulus and phase angle, they concluded that the asphalt mixture modified with fibers has a higher dynamic modulus compared to the unmodified asphalt mixture. Also, the resistance to fatigue and rutting is improved in asphalt mixture modified with fibers (S. Wu et al., 2007).

In a research conducted by Jenq and his colleagues, the fracture mechanics method was used to investigate the effect of fibers on the resistance to crack growth in asphalt mixture (Jenq et al., 1993). For this purpose, asphalt mixtures modified with two types of polyester and polypropylene fibers were evaluated in terms of modulus of elasticity, fracture energy and tensile strength. The results of this study show an increase in stiffness with a 50-100% increase in fracture energy, while the increase in fracture energy has little effect on elasticity and tensile strength. An increase in the rate of fracture stiffness parameter can indicate a higher resistance of the modified asphalt mixture to the applied loads and a higher resistance to crack growth (Cleven, 2000).

In a study, Simpson and Mahboob (1994) investigated asphalt mixtures modified with fibers and polypropylene and polyester polymers by conducting Marshall tests, indirect tensile strength, moisture and freezing sensitivity, modulus of elasticity and rutting. In their research, asphalt mixtures modified with polypropylene fibers showed higher tensile strength and cracking resistance. However, polypropylene fibers did not have an effect on improving resistance to moisture and damage caused by freezing and thawing. Also, unlike the asphalt mixtures modified with polymers and polyester fibers, the asphalt mixture containing polypropylene fibers did not have a problem in terms of thermal cracking. The results of the modulus of elasticity test showed that the asphalt mixture modified with polypropylene fibers had more stiffness and the reduction of rutting was observed only for the sample modified with polypropylene fibers (Cleven, 2000; Simpson & Mahboub, 1994).

In past researches, the use of cellulose fibers to modify the properties of bitumen has reduced the degree of penetration and increased the softening point of bitumen (Mohammed et al., 2018; M.-M. M. Wu et al., 2015). In the research conducted by Mohammad and his colleagues, the penetration degree of bitumen modified with glass fibers and cellulose fibers has decreased; however, glass fibers have a greater effect on reducing bitumen penetration. They found the shorter length of cellulose fibers than glass fibers to be effective in their less effect on reducing the degree of penetration (Mohammed et al., 2018).). Reduction of the penetration degree of bitumen modified with cellulose fibers has increased its softening point; therefore, the use of cellulose fibers can improve the properties of bitumen at high temperature. As the fibers are dispersed in the bitumen and the bitumen is absorbed by the fibers, due to the creation of a three-dimensional network in the bitumen, a strong binding force is created between the surface of the fibers and the bitumen; Therefore, by maintaining this structure at high temperature, the properties of bitumen containing fibers are also improved at high temperature (Mohammed et al., 2018; M.-M. M. Wu et al., 2015); However, the effect of fibers on the properties of bitumen depends on the characteristics of the fibers including the length and type of fibers (Chen & Lin, 2005).

In the research by Wu et al., to determine the minimum amount of fibers, the results of softening point test of the bitumen modified with fibers have been used. So, considering the maximum temperature of 60°C for asphalt pavement in summer, the minimum amount of cellulose fibers has been determined as one percent based on the softening point temperature. The minimum amount of fibers used depends on the properties of pure bitumen and the type of fibers, and therefore it is not possible to determine the minimum amount of fibers necessary to modify the properties of bitumen based on the results of past researches. One of the reasons for the effect of the type of fibers on the obtained results can be the entanglement and different involvement of various types of fibers with bitumen (M.-M. M. Wu et al., 2015).

The results of past researches indicate an increase in the viscosity of bitumen modified with fibers. Consequently, increasing the viscosity and stiffness of bitumen increases resistance to rutting of the modified bitumen (Chen & Lin, 2005; Mohammed et al., 2018); Therefore, regardless of the test temperature, the use of fibers including cellulose fibers can increase the rutting parameter compared to the bitumen without additives (Mohammed et al., 2018; Shaopeng et al., 2006; M.-M. M. Wu et al., 2015); However, the increase in resistance to rutting of modified bitumen has depended on the amount of the fibers used. For example, in a research, by comparing the bitumen modified with different amount of fibers, Shaopeng and his colleagues concluded that if the fibers in the bitumen are reduced, they do not have enough interaction with each other, and the fibers work as fillers in the bitumen. Therefore, the use of a small amount of fibers has not had much effect on increasing the amount of the mixed modulus (Shaopeng et al., 2006).

In the research conducted by Wu and his colleagues, by increasing the amount of cellulose fibers used from 4 to 6%, the rutting resistance parameter of the modified bitumen shows a greater increase. Also, compared to carbon fibers and mineral fibers, cellulose fibers have had a greater effect on improving the rutting parameter. In their research, they pointed out that cellulose fibers absorb more resin and oils in bitumen, which can be the reason for increasing the hardness and thus increasing the rutting parameter in the bitumen containing cellulose fibers (M.-M. M. Wu et al., 2015). Among the other reasons for the improvement of high functional temperature of the bitumen modified with fibers, we can mention the reduction of the phase angle. According to the results of the research conducted by Mohammad and his colleagues, cellulose fibers have has a greater effect on reducing the angle than glass fibers. Among the reasons for this is the uneven surface of cellulose fibers compared to glass fibers and the formation of cellulose fibers from smaller bundles of fibers (Mohammed et al., 2018).

Liquor can be mentioned as another used additive to improve bitumen properties. Liquor contains significant amounts of lignin, which can be used as a partial replacement of bitumen (up to 25%) or as a modifier additive in asphalt pavement. At this time, lignin can be considered as one of the most abundant biopolymers on earth with the production of about 50 to 70 million tons per year, a significant part of which is burned or discarded without being reused (Boerjan & Ralph, 2003; Mandlekar et al., 2018).

According to the results of past researches, the use of lignin can improve the properties of bitumen. Bitumen containing lignin has a higher viscosity than pure bitumen. This increase is dependent on the amount of the lignin consumed, and the viscosity of bitumen increases in proportion to the amount of lignin (Sundstrom et al., 1983; Terrel & Rimsritong, 1979). As the viscosity increases, the rutting resistance of the bitumen modified by lignin also increases (McCready & Williams, 2008).

In the research conducted by Zareii et al., black liquor with different weight percentages (2, 4, 6, and 8%) was used to modify the properties of 60/70 bitumen of Isfahan Refinery, and the effect of this additive on various properties of bitumen was investigated. The results of their research indicate the improvement of the characteristics and performance of the modified bitumen at high temperature. The addition of black liquor to pure bitumen has decreased the degree of penetration, increased kinematic viscosity, increased softening point and decreased thermal sensitivity of bitumen (Zarei et al., 2017). In past researches, the improvement of bitumen properties was dependent on the amount of additive, and the use of lignin in an amount less than 3% did not affect the functional properties of bitumen. Also, an increase of more than 6% of lignin caused a significant increase in bitumen hardness and had a negative effect on the low-temperature performance of bitumen (Zahedi et al., 2020).

In another study, Wang and his colleagues investigated the rheological properties of bitumen modified with lignin in vitro. In this research, two types of bitumen with performance grade of PG 64-22 and PG 76-22 were combined with two different percentages of lignin (5 and 10% of weight) and the rheological properties of the samples were evaluated. The results of the dynamic shear rheometer test showed that increasing the amount of lignin improved the resistance to rutting and increased the high-temperature performance of bitumen. They stated that the lignin in the liquor does not just act as filler but chemically reacts with the bitumen (Wang & Derewecki, 2013).

Su et al. (2017), investigated in a study the rheological properties and anti-aging performance of the bitumen modified with lignin. They concluded that the use of lignin has increased the viscosity and the resistance to rutting of bitumen; however, the appropriate viscosity amount for mixing and densification of bitumen has been met according to the Superpave Mix Design for hot asphalt production. The results obtained from the bending beam rheometer test and the linear range sweep test showed that lignin had a small negative effect on the bitumen's low-temperature performance and fatigue resistance. So that the fatigue life of bitumen modified with lignin has been reduced especially at lower strain level (Xu et al., 2017).

Among the other reasons for using lignin as a bitumen modifier, we can mention the antioxidant property of lignin due to its polyphenolic structure and control of free radicals, which has led researchers to use this additive to improve the aging or brittleness of bitumen due to oxidation and or loss of volatile substances (Bishara et al., 2005).

According to the results of Su and his colleagues' research, lignin can help resist the formation of carbonyl functional groups in the modified bitumen after short-term and long-term aging; therefore, lignin can be used as an antioxidant to reduce the negative effects of aging in bitumen and asphalt mixture (Xu et al., 2017).

According to the important role of economic parameters and environmental issues in the evaluation of engineering projects, it is necessary to consider the economic and environmental aspects in selecting additives in addition to their effect on improving pavement performance and durability. Compared to polymer additives, the use of cellulose fibers as an additive in improving the properties of bitumen and asphalt mixture has advantages such as a more reasonable price and a lower temperature required for mixing and compaction; Therefore, in this research, the waste of paper factories, including cellulose micro-fibers obtained from pulp and liquor mills, along with their combination, has been used to modify the properties of base bitumen. The use of waste materials can be cost-effective and improve the performance characteristics of bitumen. Considering the need to build new roads and the increase in fuel costs and the pollution caused by the production and implementation of asphalt mixture, the use of waste from paper production factories can be a low-cost and suitable solution to reduce the problems and failures of asphalt pavement.

2. Methodology

2.1. Materials

In this research, in addition to the effect of additives on the modification of bitumen properties, special attention has been paid to economic aspects and environmental issues. Due to the significant volume of paper factory wastes and aiming at reusing these wastes, in this research paper pulp and liquor have been used as additives to modify the properties of base bitumen. Thus in addition to improve the properties of bitumen, it has been tried to sustainably use the production wastes of paper factories.

2.2. Bitumen

In this research, for the base bitumen, the bitumen produced by Jey oil refining company with a performance grade of PG 64-16 according to the specifications presented in Table 1 was used.

2.3. Additives

The liquor used in this research was obtained from the waste of Mazandaran wood and paper factory with the specifications presented in Table 2. In this research, the black liquor was heated indirectly (with a maximum temperature of 110 degrees Celsius) and the powder that remained after passing through the sieve 30 was used as an additive to the bitumen to avoid a SHRP increase in the volume of bitumen during mixing due to the liquid state of the black liquor and reduce its impurity. Compared to the liquid state, this powder contains significant amounts of lignin, which may have a greater effect on improving the performance properties of bitumen and asphalt mixture.

Paper pulp has been prepared from the waste of Barghdaran Sanat company, with an average fiber length of 0.2 mm. Like liquor, this additive has been used in a oven for 24 hours at a temperature of 110 degrees Celsius, after complete drying and reducing its dimensions by an industrial mill for mixing with bitumen.

Table 1. Properties of the base binder

Humidity: 20 % Pressure: 630 mmHg Temperature: 25 ºC

No	Test	Standard Range		Result	Test Meted
		Max	Min		
1	Viscosity @ 135C	3 Pa.s	--	0.326	ASTM D4402
2	Flash Point Temp.	--	230ºC	334	ASTM D92
3	Orig. Dynamic Shear G*/sinδ ,Test Temp at 10 rad/s (ºC)	--	1.00 kPa	1.57	AASHTO T315
4	RTFO Percent Change	1.0%	--	0.048	ASTM D2872
5	RTFO Dynamic Shear G*/sinδ ,Test Temp at 10rad/s(ºC)	--	2.20kPa	3.36	AASHTO T315
6	PAV@100(ºC) Dynamic Shear G*.sinδ .Test Temp at10 rad/s(ºC)	5000 kPa	--	4920	AASHTO T315
7	PAV Creep Stiffness S. Test Temp (ºC) @ 60 s	300 Mpa	--	114.33	ASTM D6648
8	m-value, (slope)	--	0.300	0.3179	ASTM D6648
9	PAV Direct Tension,Failure Strain ,Test Temp@ 1.0 mm (ºC)	--	1.0%	--	AASHTO T314
Performance Grade Bitumen: PG 64-16					

Table 2. black liquor analysis

<table>
<tr><td>Total Solids</td><td rowspan="4">%</td><td>3.66</td></tr>
<tr><td>Ash</td><td>24.8</td></tr>
<tr><td>Organics</td><td>75.2</td></tr>
<tr><td>Lignin</td><td>20.2</td></tr>
<tr><td>Residual Soap</td><td rowspan="11">mg/kg</td><td>0.29</td></tr>
<tr><td>Total Oxalate</td><td><50</td></tr>
<tr><td>chloride</td><td>37</td></tr>
<tr><td>Calcium</td><td>98</td></tr>
<tr><td>Sodium</td><td>5070</td></tr>
<tr><td>Sulphur</td><td>3230</td></tr>
<tr><td>Potassium</td><td>270</td></tr>
<tr><td>Mgnesium</td><td>36</td></tr>
<tr><td>Phosphorus</td><td>22</td></tr>
<tr><td>Nickle</td><td>5.9</td></tr>
<tr><td>Silicon</td><td>10</td></tr>
<tr><td>Manganese</td><td></td><td>3.6</td></tr>
<tr><td>Iron</td><td></td><td>1.6</td></tr>
<tr><td>Zinc</td><td></td><td>0.8</td></tr>
<tr><td>Aluminium</td><td></td><td>0.7</td></tr>
<tr><td>Stronsium</td><td></td><td>0.7</td></tr>
<tr><td>Brium</td><td></td><td>0.9</td></tr>
</table>

2.4. Mixing Bitumen and Additives

The appropriate amount of each additive has been selected based on past studies and the results of preliminary tests. Considering that the use of liquor and paper pulp with an amount of less than 3% cannot have much effect on improving the properties of bitumen and asphalt mixture, Therefore, according to Figure 1, choosing the optimal percentage of cellulose fibers, 4, 6, and 8 percent of cellulose microfibers have been used to modify the properties of bitumen. Choosing 8% of fibers is to determine the optimal percentage of cellulose fibers in order to show clearly the effect of a large amount of fibers in bitumen (Andrés-Valeri et al., 2018; Gupta et al., 2019; Zahedi et al., 2020).

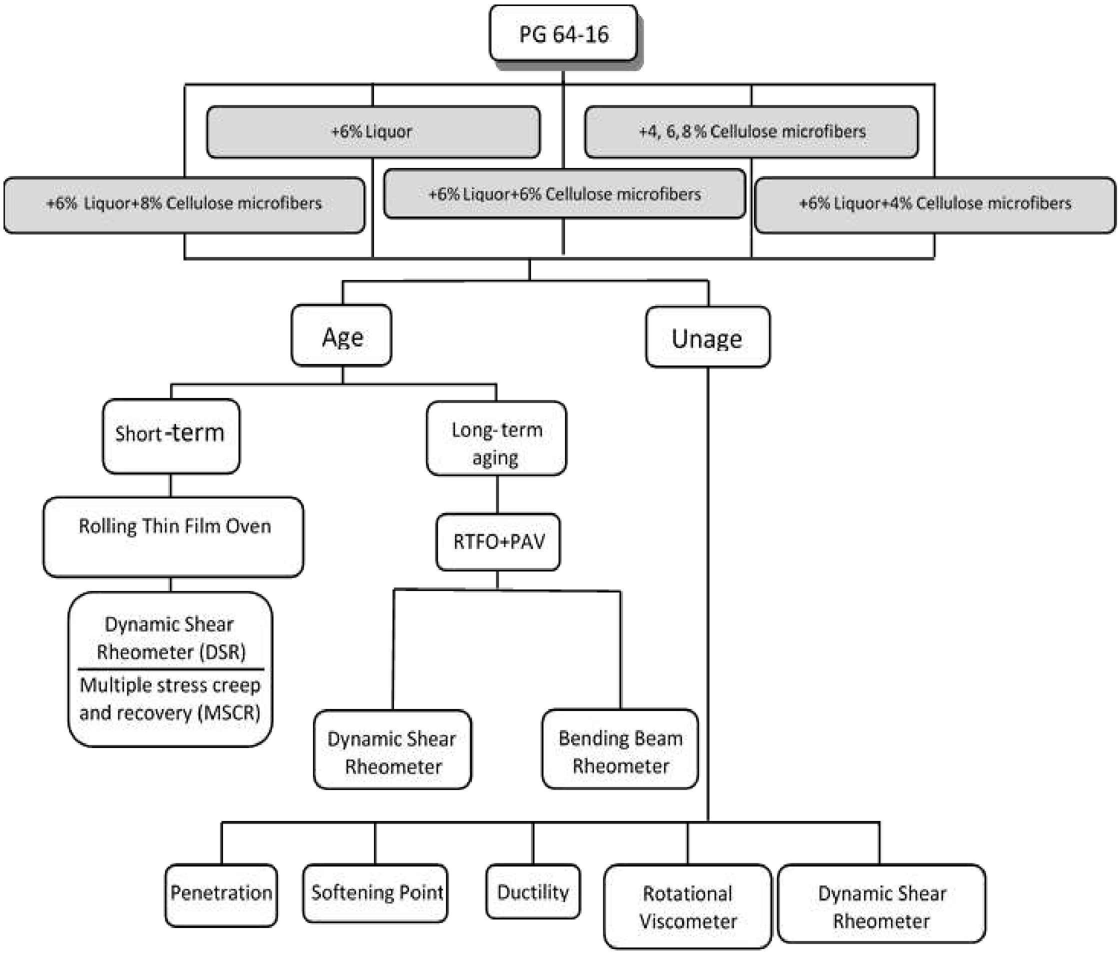


figure 1. Experimental flow chart

Due to the limitation of the particle size of modifiers in the dynamic shear rheometer test, grinding was used to reduce the size of additives (liquor and paper pulp) to less than 250 microns so that this test could be performed on the modified bitumen (Read & Whiteoak, 2003). For this purpose, the additives were first placed at 110°C for 24 hours and after complete drying, the mill has been used to reduce the dimensions of the additives. Due to the solid and insoluble nature of the additives, high shear mixer has been used for homogeneous mixing of lignin and bitumen in past researches (Lynam et al., 2018); Therefore, similar to the research conducted in this field (Arafat et al., 2019; J. Wu et al., 2021), in this research, for mixing bitumen with additives, the high shear mixer according to Figure 1, with the speed of 2500 cycles per minute has been used. Bitumen and additives were mixed at 160°C for 60 minutes.

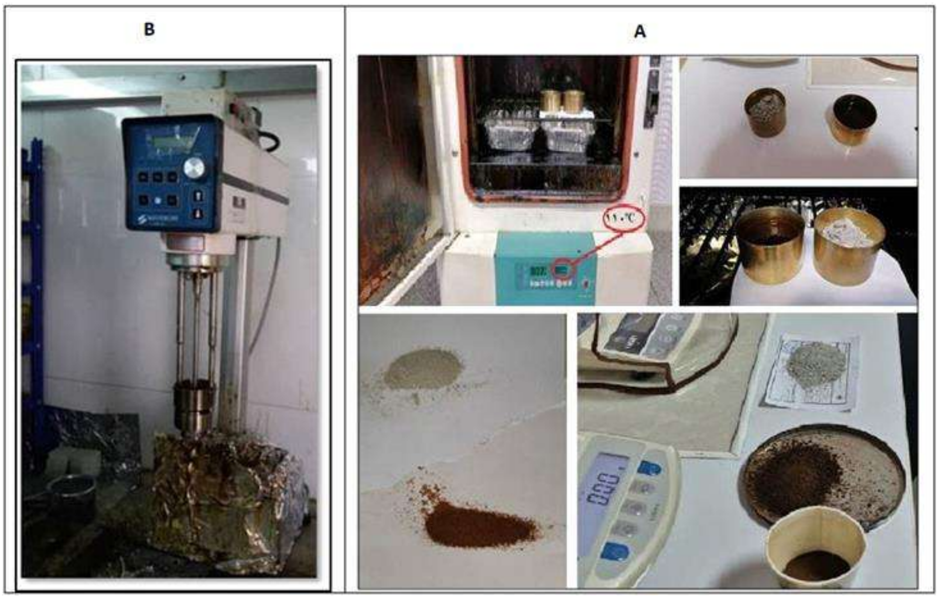


Figure 2. a: preparation of additives b: high shear mixer

2.5. Penetration Degree and Softening Point Tests

Common tests of bitumen, including penetration degree and softening point according to ASTM-D5 and ASTM-D36 standards were performed to determine the physical properties of modified bitumen; In addition, by comparing the penetration index value for base bitumen and modified samples, the effect of additives on the thermal sensitivity of bitumen was investigated. To determine the temperature sensitivity of bitumen, the equation developed by Pfeiffer and Van Doormaal in 1936 was used (Pfeiffer & Van Doormaal, 1936).

in which:

A: temperature sensitivity, PI: penetration index and $T_{R\&B}$: softening point temperature.

$$A = \frac{\log 800 - \log(\text{ pen at } 25°C)}{T_{R\&B} - 25°C} \quad (1)$$

$$PI = \frac{20 - 500\,A}{1 + 50A} \quad (2)$$

The results of penetration degree and softening point tests according to Figure 2 show an increase in bitumen hardness in all modified samples.

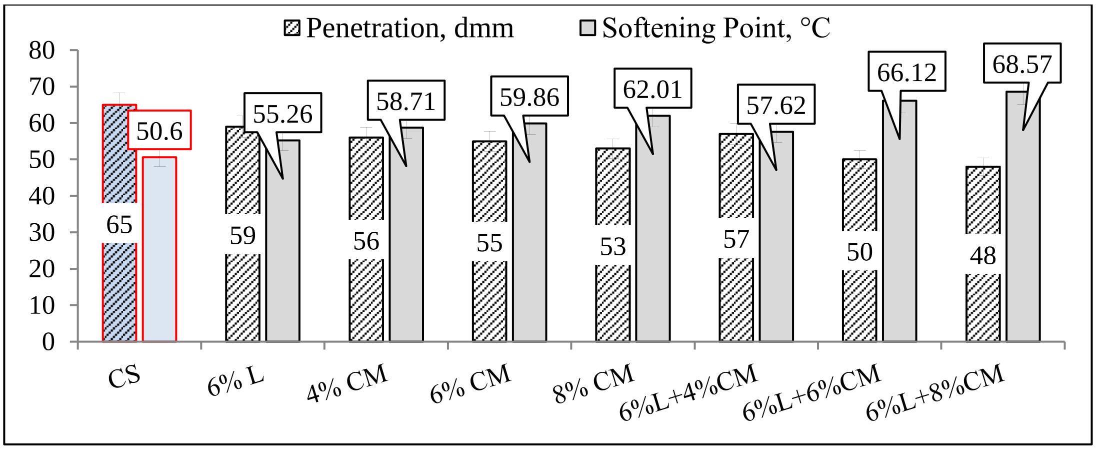


Figure 3. Penetration degree and softening point

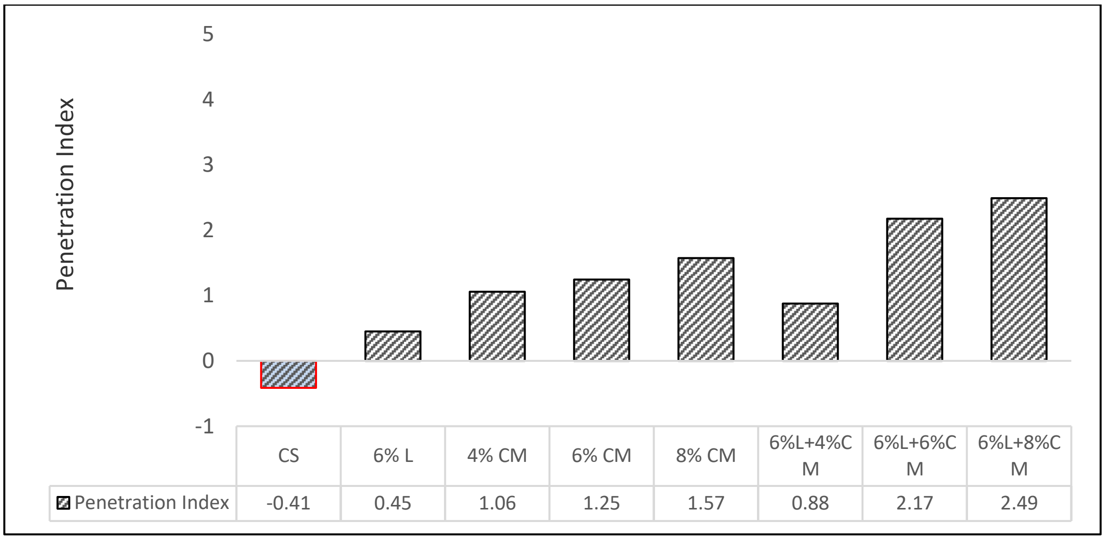


Figure 4. Penetration index

Choosing the proper degree of penetration for bitumen based on the life and performance of the pavement is very important. If the area faces a hotter climate or heavier and more frequent traffic conditions, it is necessary to use bitumen with a lower degree of penetration. The results of the tests according to Figure 3 have shown that among the investigated additives, the combination containing 6% liquor with 8% cellulose micro-fibers had the greatest effect on the softening point (about 35% increase) compared to the base bitumen. The increase in hardness of bitumen has a direct relationship with the amount of the additive, and with the increase in the amount of cellulose fibers from 6 to 8% of weight, the hardness of bitumen has also increased.

By reducing the penetration degree of the bitumen modified with cellulose micro fibers, its softening point has increased; therefore, the use of cellulose fibers can improve the properties of the modified bitumen at high temperature. As the fibers are dispersed in the bitumen and the bitumen is absorbed by the fibers, due to the creation of a three-dimensional network in the bitumen, a strong binding force is created between the surface of the fibers and the bitumen; Therefore, by maintaining this network at high temperature, the properties of the bitumen containing fibers are also improved at high temperature (Pamplona et al., 2012; M.-M. M. Wu et al., 2015).

Softening point is used in determining bitumen permeability (PI). The temperature sensitivity of bitumen depends on the sign and magnitude of penetration index, which for the bitumen used in road construction, the appropriate value of penetration index is in the range of 2 to 2-. The increase in penetration index indicates the improvement of temperature sensitivity of bitumen; in all amounts of additives, the value of penetration index has increased compared to the base bitumen. As shown in Figure 4, the penetration index of the modified bitumen increased by about 86 to 290% compared to the base bitumen; therefore, it can be concluded that the thermal sensitivity of the modified bitumen and their performance in different temperature conditions have been improved.

2.6. Ductility Test

To check the adhesion of bitumen, ductility test has been used according to ASTM-D113 standard. In this test, the bitumen sample is stretched at a temperature of 25°C at a constant speed of 50 mm/min, and the amount of bitumen elasticity is determined by measuring the elongation of the bitumen sample before tearing (in centimeters). As it can be seen in Figure 5, the ductility property of all samples modified with cellulose fibers and liquor has decreased. According to the direct relationship between bitumen ductility and its adhesive property, it can be concluded that the adhesive property of the modified bitumen has decreased.

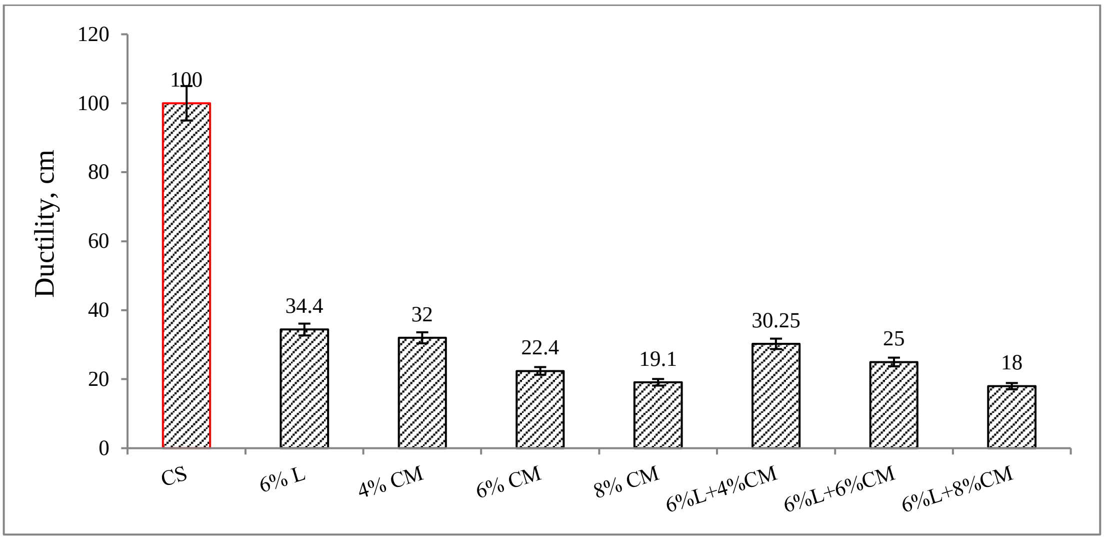


Figure 5. Ductility

2.7. Rotational Viscosity Test

In order to evaluate the efficiency and determine the proper mixing temperature and density of bitumen, rotational viscosity test was used according to AASHTO T316-04 standard. Determining bitumen viscosity is very important because of its role in bitumen pumping and moving, as well as in determining the mixing temperature and density of asphalt mixture. This test was conducted at four temperatures of 100, 135, 160 and 180 degrees Celsius to investigate the effect of each additive on bitumen viscosity at different temperatures.

As shown in Figure 6, and as it was expected, the viscosity of all the modified samples increased. Meanwhile, cellulose micro-fibers have had a greater effect on increasing the viscosity of bitumen. The increase in viscosity has a direct relationship with the additive percentage, and with the increase in the additive percentage, the bitumen viscosity has increased too. Among the investigated additives, the combination containing 6% of liquor with 8% of cellulose micro fibers has had the greatest effect on increasing the viscosity of bitumen with a 197% increase in viscosity at 135°C compared to the base bitumen.

According to Table 3, based on ASTM D6926-04 standard and according to the values of **170±20** and **280±30** centistokes, for the proper mixing and compaction temperature of bitumen, it can be concluded that the mixing and compaction temperature of all the modified samples has increased compared to the base bitumen, so that the mixing temperature of the modified bitumen increased 2.2 to 10.3 °C and their compaction temperature increased 4.3 to 17.1 °C compared to the base bitumen. However, this increase was higher in the bitumen modified with the combined addition of liquor and cellulose fibers.

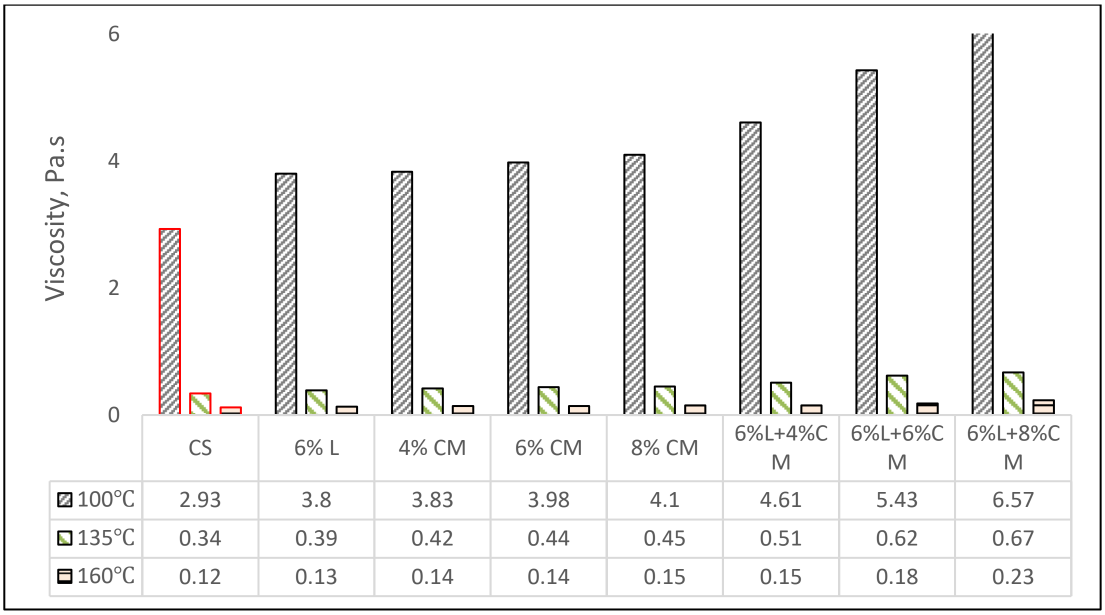


Figure 6. The results of rotational viscosity test

Table 3. Mixing and compaction temperatures for unmodified and modified binders

Components	Mixing Range (°C)	Mixing Temperature changes (°C)	Compaction Range (°C)	Compaction Temperature changes (°C)
CS	156.6-152	-	145.2-138.4	-
6% L	158.1-154.2	+2.2	148.5-142.7	+4.3
4% CM	159.1-155.5	+3.5	150.2-144.8	+6.4
6% CM	159.2-155.8	+3.8	150.8-145.8	+7.4
8% CM	160-156.7	+4.7	151.7-146.7	+8.3
6%L+4%CM	160-157.2	+5.2	153.1-148.9	+10.5
6%L+6%CM	161.7-159.4	+7.4	156-152.6	+14.2
6%L+8%CM	164.5-162.3	+10.3	158.9-155.5	+17.1

2.8. High-Temperature Performance

To describe the viscoelastic behavior of bitumen in the temperature range of 3 to 88 degrees Celsius (middle and high temperature), a dynamic shear rheometer device is used according to the AASHTO M-320 standard. In this experiment, two parameters of total shear stress modulus (G*) and phase angle (δ) which are determined based on shear force applied by the machine are used to describe both viscous and elastic behavior of bitumen. The high and medium temperature performance of bitumen will be determined based on the rutting parameter G*/sinδ (as a measure against bitumen deformation and stiffness) and comparing its value with the standardized limits. For high-temperature performance, the value of this parameter should not be less than 1000 pascals for un-aged bitumen and 2200 pascals for aged bitumen in the rotary thin glaze test. It should be noted that conducting this test and its acceptable results depend on compliance with the size limit of bitumen particles; Therefore, the investigated bitumen should not contain particles with dimensions greater than 250 microns (250 m = ¼ mm).

According to Figures 7 to 11, the rutting parameter has been increased in all modified samples in both un-aged and short-term aged states; however, only in the modified samples with the combined addition of liquor and cellulose fibers, the increase in the Rutting parameter has led to an increase in the high-temperature performance of the bitumen sample. One of the reasons for the increase in the rutting parameter in the combined samples can be the increase in hardness in these samples, which has finally led to the improvement of the high-temperature performance in the modified samples by affecting the phase angle.

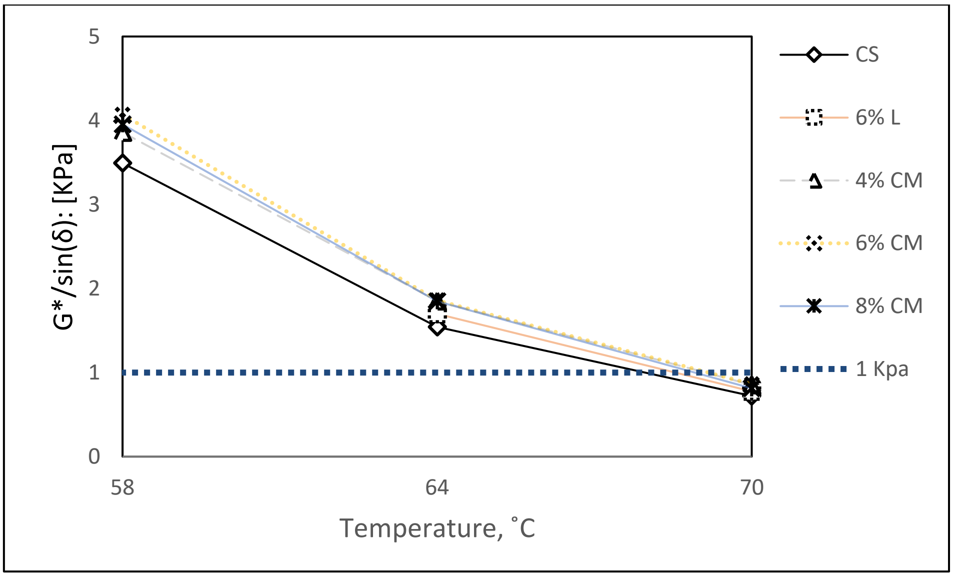


Figure 7. Rutting parameter of the samples modified with liquor and cellulose microfibers in the un-aged state

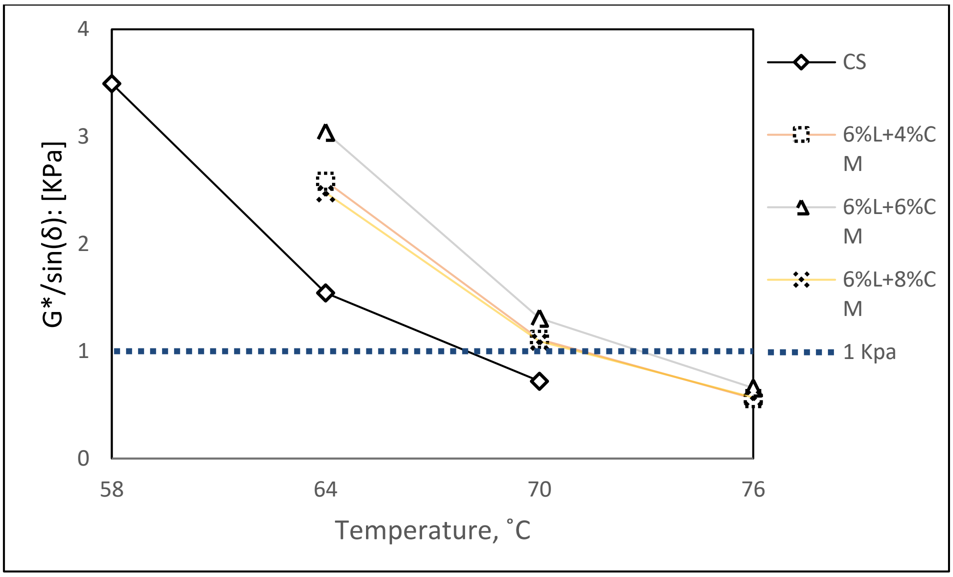


Figure 8. Rutting parameter of the samples modified with the combined additive of liquor and cellulose microfibers in the un-aged state

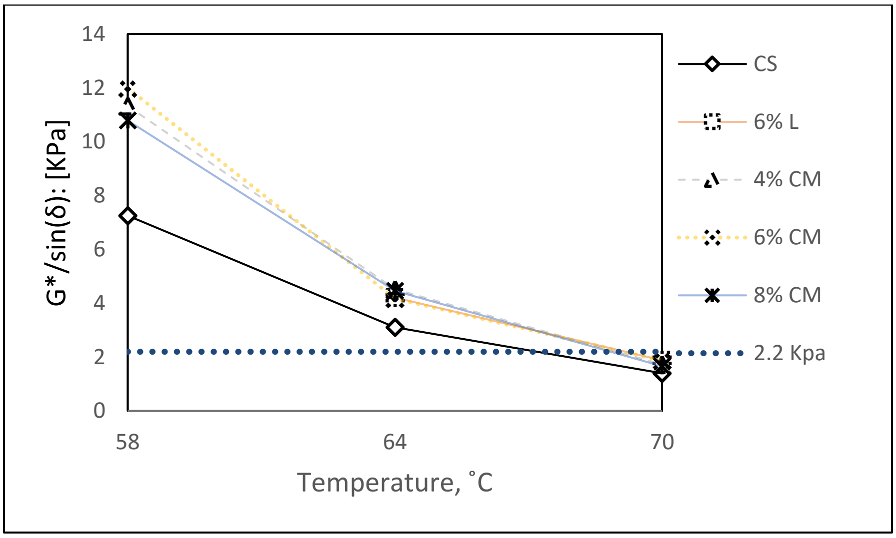


Figure 9. Rutting parameter of the samples modified with liquor and cellulose micro-fibers in a short-term aged state

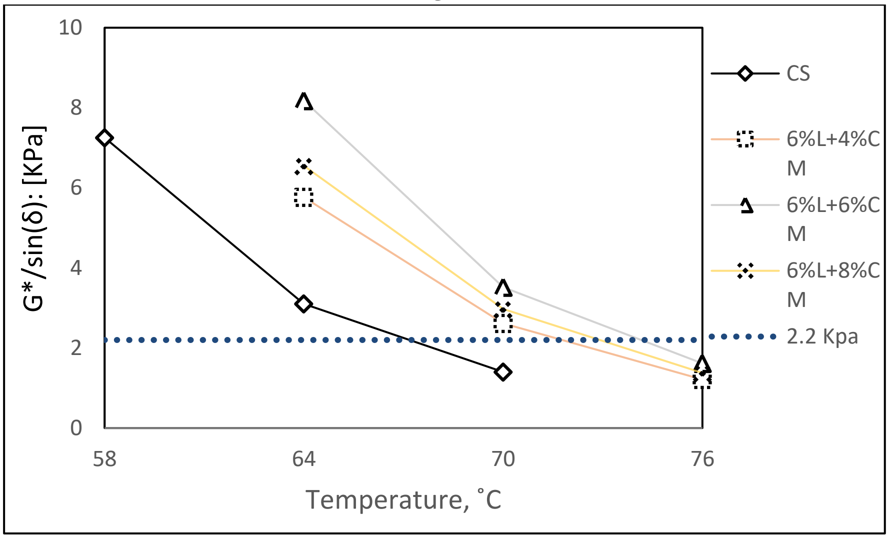


Figure 10. Rutting parameter of the samples modified with the combined additive of liquor and cellulose micro fibers in the short-term aged state

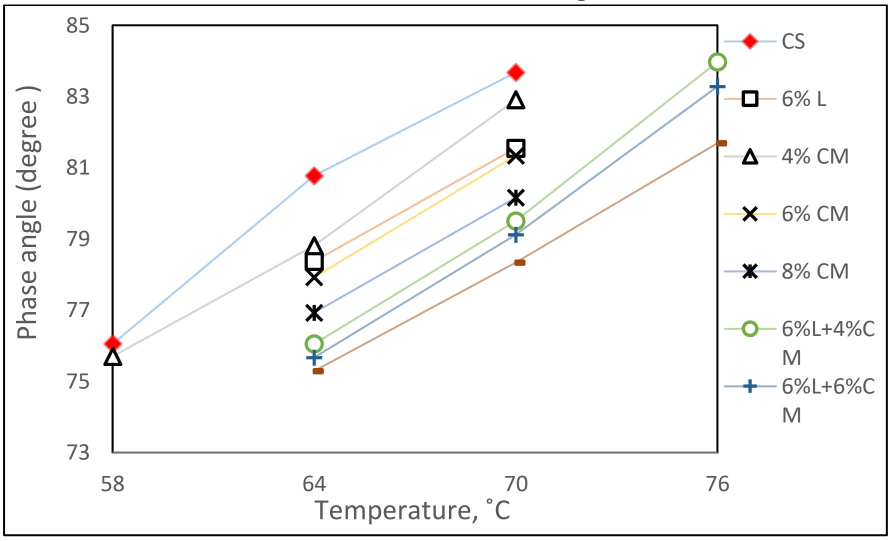


Figure 11. Phase angle changes for the base bitumen and the modified bitumen from 58 to 76°C (un-aged)

2.9. Multi Stress Creep and Recovery

The inability of conventional bitumen tests to fully describe the properties of the modified bitumen has led researchers to use SHRP Plus tests, including Multi Stress Creep and Recovery tests at several stress levels in accordance with the AASHTO T350 standard, in order to investigate and describe the properties of the modified bitumen. In the dynamic shear rheometer test, the parameters of mixed modulus and phase angle are measured in the linear range (viscosity-elasticity) and bitumen flow is considered linear and does not depend on the stress level; however, this assumption is not correct for the modified bitumen and the amount of stress applied during the experiment influences on the obtained results. The creep and return test at several stress levels is performed similar to the dynamic shear rheometer test, with a difference in how the loading is applied. This test includes 1 second of loading and 9 seconds of unloading at the stress levels of **1/0** and **2/3** kPa in 10 cycles for each stress level. The results of this test, including the irreversible softening (Jnr) as well as the return percentage (R) in each cycle, are used to check the high performance temperature of the asphalt mixture. As shown in Figures 12 and 15, cellulosic fibers have been able to improve the bitumen return percentage at both stress levels and also reduce the irreversible softness in the modified bitumen compared to the base bitumen. The decrease in Jnr parameter indicates an increase in the resistance to rutting in the samples modified with cellulose fibers, and its amount depends on the type and percentage of the added fibers; however, Jnr parameter in the bitumen modified with the combined additive of cellulose micro-fibers and liquor has increased at the stress level of 2/3 kPa compared to the sample containing only cellulose micro-fibers, as well as an increase of more than 6% of cellulose micro-fibers in the combined samples due to an extreme increase of the stiffness of bitumen has caused the sensitivity of the sample to increase the stress level; So that in these samples, the changes of the irreversible softening parameter, i.e. $J_{nr\ difr}$, are more than 75%.

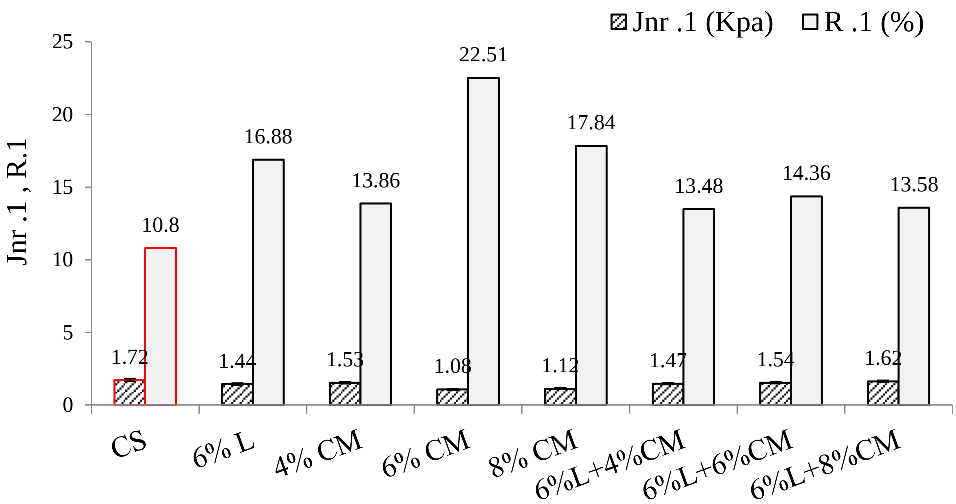


Figure 12. Irreversible softening parameter and return percentage (stress level 1/0 kPa and temperature 64 degrees Celsius)

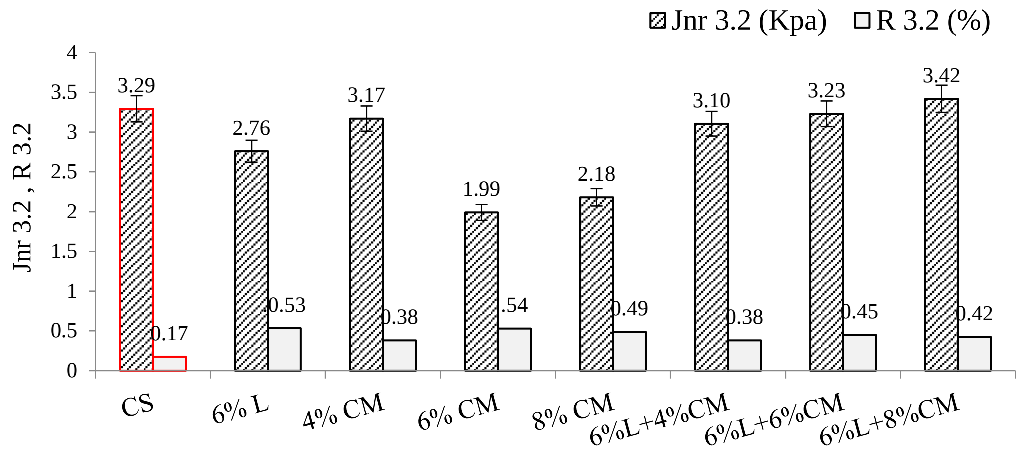


Figure 13. Irreversible softening parameter and return percentage (stress level 2.3 kPa and temperature 64°C)

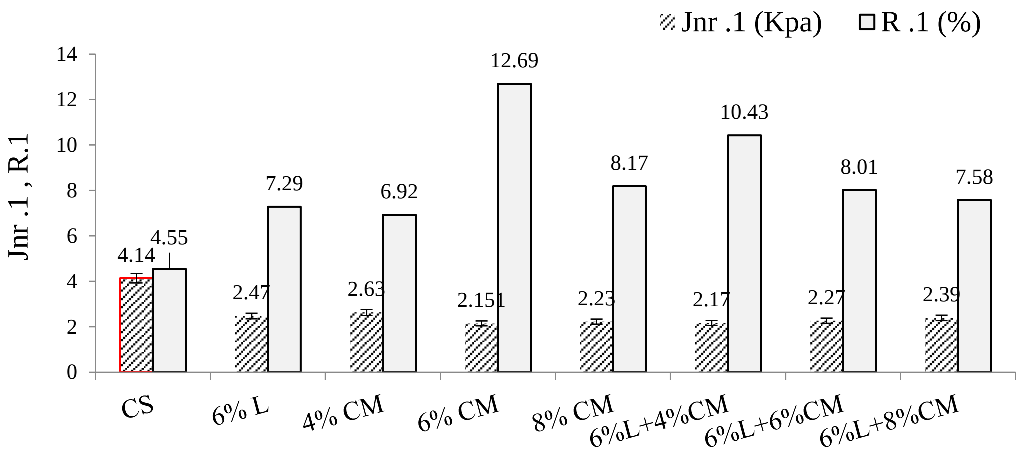


Figure 14. Irreversible softening parameter and return percentage (stress level 1/0 kPa and temperature 70°C)

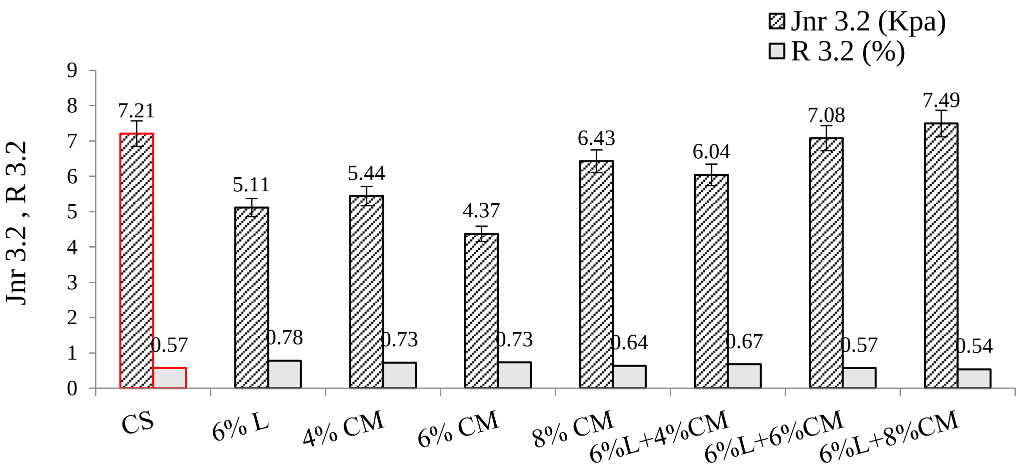


Figure 15. Irreversible softening parameter and return percentage (stress level 2.3 kPa and temperature 70°C)

2.10. Linear Amplitude Sweep Test

To evaluate the bitumen fatigue behavior, the linear amplitude sweep test according to AASHTOTP-101 standard has been used. This test was performed with a dynamic shear rheometer device and with a spindle with a diameter of 8 mm on short-term aged bitumen. The linear amplitude sweep test consists of two stages. The first step, the frequency sweep, is designed to obtain information about the bitumen's rheological properties. In this stage, loading is done with constant strain and with a wide range of frequencies from 1/0 to 30 Hz. By determining the shear complex modulus and the phase angle at each frequency, the storage modulus and finally the failure analysis parameter (α) will be obtained. In the second stage, i.e. strain sweep, loading is performed with a constant frequency of 10 Hz and with a linear change of the strain amplitude from 1/0 to 30%.

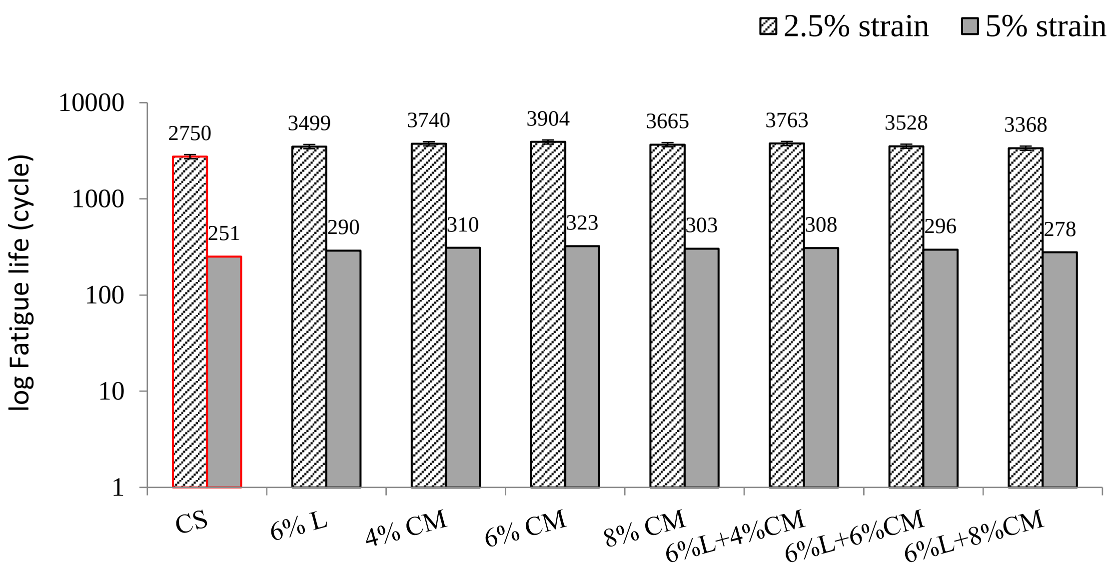


Figure 16. Fatigue life of RTFO-aged samples at 2.5% and 5% strain amplitude

By analyzing the outputs of linear amplitude sweep test, the fatigue life of bitumen and the modified samples was determined based on viscoelastic cumulative failure method. According to Figure 16, the results show improved fatigue life in the modified samples; however, the upward trend of fatigue life has been stopped with an increase of more than 6% of cellulose micro fibers. The data obtained from this experiment confirm the results of SHRP tests with the same trends but at different levels.

2.11. Low-Temperature Performance

Bending beam rheometer test is performed in order to measure the amount of fluctuation or creep of bitumen under constant load and constant temperature, on the aged bitumen under short-term aging and long-term aging. In this test, the values of two parameters, creep hardness and m-value, which respectively indicate bitumen resistance against creep loading and changes in bitumen hardness during loading, are measured and reported at the times of 8, 15, 30, 60, 120, and 240 seconds. According to AASHTO T313 standard, m-value in 60 seconds should be greater than or equal to 3/0 and the value of creep hardness should not exceed 300 MPa in 60 seconds. According to the obtained results, the value of creep hardness in all samples has been lower than the standard limit of 300 MPa; therefore, in this research, only the results of m-value parameter have been used.

As it can be seen in Figure 17, except for liquor, which had a negative effect on the low-temperature performance, m-value has increased in the samples modified with other additives. Among the studied samples, the use of 6% cellulose micro fibers has had the most positive effect on the low-temperature performance of the bitumen, so that the low performance temperature of this combination has improved one level higher than the basic bitumen (from 16-°C to 22-°C). The use of cellulose microfibers in the sample mixed with liquor has been able to reduce the negative effect of liquor on the low-temperature performance to some extent. The creep stiffness of the samples modified with cellulose microfibers has increased corresponding to the results obtained for the penetration degree and the softening point; however, despite the increase in the hardness of the bitumen modified with fibers, due to the increase of the m-value parameter, the Low-temperature performance of the bitumen modified with cellulose microfibers has been improved.

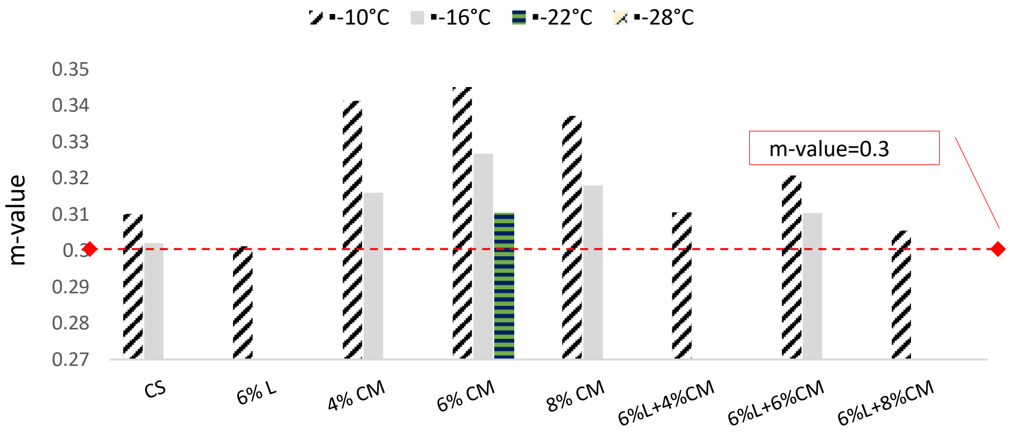


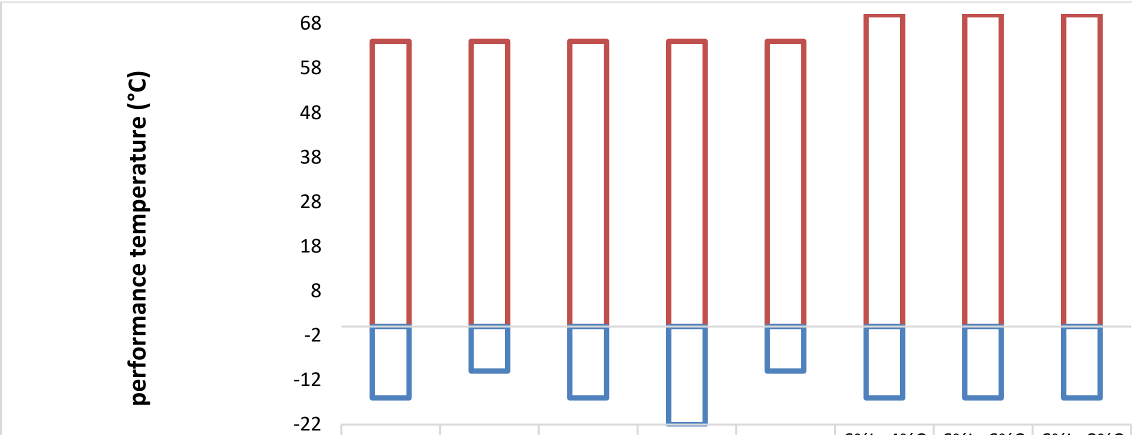
Figure 17. Changes in the m-value parameter for each combination

2.12. Performance Grades of Samples

According to the obtained results, the properties of bitumen modified with cellulose fibers have been improved; however, it is not recommended to add more than 6% of cellulose micro-fibers in order to modify the properties of bitumen. In this research, the use of 6% cellulose fibers compared to 8% cellulose microfibers has had a more positive effect on the properties of the modified bitumen.

According to Figure 19, the use of liquor in combination with cellulose microfibers has improved the high-temperature performance to one-step from 64 to 70 degrees Celsius. One of the reasons for the improvement of the high-temperature performance of the modified samples can be the increase of the stiffness of these samples. The results of the past researches also support the increase in stiffness of bitumen modified with cellulose fibers (Li et al., 2021; Mohammed et al., 2018; M.-M. M. Wu et al., 2015), so that in the research of Mohammed and his colleagues, the use of two percent of cellulose fibers has increased the softening point temperature of bitumen from 52 to 59 degrees Celsius (Mohammed et al., 2018). In this research, the use of 6% of pure cellulose microfibers has increased the softening point by 9.26 degrees Celsius compared to the base bitumen.

The difference in the obtained results can be due to the difference in the type of cellulose fibers used in the research of Mohammad and his colleagues, as well as the size of the fibers used (20 to 2500 micrometers long and 25 micrometers wide) compared to the present research.



	CS	6% L	4% CM	6% CM	8% CM	6%L+4%CM	6%L+6%CM	6%L+8%CM
high-temperature performance	64	64	64	64	64	70	70	70
low-temperature performance	-16	-10	-16	-22	-10	-16	-16	-16

Figure 18. performance grades of samples

In Table 4, the zoning of the suitable bitumen based on performance (PG) for the provincial centers of the country has been given. The results of this research showed that by using liquor and cellulose fibers, it is possible to obtain several types of modified bitumen (several performance categories) at a low cost, which can provide several choices for selecting modified bitumen according to the temperature conditions of each region for the officials and contractors of bitumen and asphalt industry of the country. According to the average air temperature of the centers of Iran's provinces during summer and winter, it is possible to provide suitable bitumen zoning based on the following temperatures:

1. Northern provinces (such as Gilan, Mazandaran, Golestan, etc.), which have cold winters and mild summers; for these areas, the bitumen with normal winter temperature (-10 degree Celsius) and normal summer temperature (58-64 degrees Celsius) (i.e. samples of 6%L and 8%M) will be suitable.

2. Eastern provinces (such as Razavi Khorasan, North Khorasan, Sistan and Baluchistan, etc.) which have cold winters and hot and dry summers; for these regions, high temperature bitumen (64 degrees Celsius) is used in summer and low temperature (-16 degrees Celsius) is used in winter. Samples of 4%CM can be used in these areas.

3. Western provinces (such as Kurdistan, West Azarbaijan, Kermanshah, etc.), which have cold winters and mild summers; for these regions, the bitumen with winter temperature (-16 degrees Celsius) and summer normal temperature (64 degree Celsius) will be suitable.

4. Southern and southwestern provinces (such as Fars, Kerman, Bushehr, etc.), which have mild winters and very hot and dry summers; for these areas, the bitumen with high temperature (70 degrees Celsius) and normal temperature (-16 degrees Celsius), i.e. samples of 6%L+6%CM, 6%L+8%CM and 6%L+4%CM can be used in summer and winter respectively.

Other factors such as asphalt characteristics (including traffic, vehicle weight, etc.) as well as the specific needs of each area can play a role in choosing the proper bitumen based on environmental conditions.

Table 4. The minimum and maximum suitable pavement temperature for the centers of the provinces of Iran based on air temperature (https://pgi.bhrc.ac.ir/)

	Minimum air temperature, at 98% confidence level (°C)	maximum air temperature, at 98% confidence level (°C)	Minimum pavement temperature, at 98% confidence level (°C)	maximum pavement temperature, at 98% confidence level (°C)
Eastern Azarbaijan	64	-16	59.82	-15.38
Western Azerbaijan	58	-16	57.21	-15.2
Ardabil	58	-22	55.18	-20.77
Esfahan	64	-10	62.5	-9.49
Alborz	64	-16	61.25	-12.14
Ilam	64	-16	62.71	-10.14
Bushehr	64	-10	63.56	4.72
Tehran	64	-10	62.6	-4.96
Chaharmahal and Bakhtiari	64	-28	59.02	-24.25
southern Khorasan	64	-16	63.43	-12.86
Khorasan Razavi	64	-16	61.15	-15.3
North Khorasan	64	-16	59.6	-14.93
Khuzestan	76	-10	71.17	0.31
Zanjan	64	-22	59.19	-19.83
Semnan	64	-10	63.43	-6.49
Sistan and Baluchestan	64	-16	63.29	-10.44
Fars	64	-10	63.33	-6.08
Qazvin	64	-16	60.8	-13.99
Qom	70	-16	65.32	-11.66
Kurdistan	64	-16	62.53	-15.19
Kerman	64	-16	62.58	-13.32
Kermanshah	64	-16	63.57	-12.92
Kohgiloyeh and Boyerahmad	64	-10	61.08	-9.76
Golestan	64	-10	61.37	-5.27
Guilan	58	-10	57.81	-6.76
Lorestan	70	-10	64.54	-8.84
Mazandaran	64	-10	60.14	-3.16
Central	58	-16	56.4	-12.33
Hormozgan	70	-10	67.59	4.43
Hamedan	64	-28	59.68	-22.69
Yazd	70	-10	66.07	-7.95

3. Statistical Analysis

In this study, Pearson's correlation analysis was conducted aiming at investigating the effect of cellulose fibers on the characteristics of the modified bitumen. SPSS22 software was used to perform this analysis. According to the results of the tests, only the effect of cellulose fibers was investigated in the tests of penetration degree, softening point and rotational viscosity. The different effect of 8% fibers caused a limitation in performing Pearson analysis for the results of other tests, including high functional temperature and low functional temperature. According to Table 5, the results show a significant relationship (Sig < 0.05) of the amount of the added fibers with changes of the degree of penetration, softening point and viscosity of the modified bitumen.

Also, the amount of Pearson Correlation indicates a strong correlation among the variables.

Table 5. Pearson analysis and investigation of the influence of cellulose fibers on bitumen properties

Factor	Characteristics	Sig.	Pearson Correlation
cellulose fibers	Penetration degree	0.004	-0.879
	softening point	0.005	0.873
	viscosity (135˚C)	0.053	0.70

4. Discussion

All the additives examined in this research have increased the hardness of the modified samples; this increase is evident in the samples modified with a high percentage of cellulose fibers. One of the reasons for improving the performance temperature of the bitumen modified with cellulose microfibers is the role of fibers in transferring and dispersing stress and preventing excessive stress concentration. Also, with the absorption of bitumen by the fibers, due to the creation of a three-dimensional network in the bitumen, a strong connection force is created between the surface of the fibers and the bitumen; therefore, by maintaining this network at high temperature, the properties of the bitumen containing fibers are also improved at high temperature (Mohammed et al., 2018; M.-M. M. Wu et al., 2015).

Nevertheless, the modified bitumen must maintain its elastic property to some extent so that it does not suffer premature failure during successive loading (Bessa et al., 2019). Excessive increase of fiber amount can have a negative effect on the properties of the modified bitumen, so that the functional temperature of the samples containing 8% cellulose microfibers has been reduced compared to the sample containing 6% cellulose fibers. The results of the linear amplitude sweep test also show a decrease in fatigue life in the samples containing 8% cellulose microfibers. The negative effect of the large amount of fibers on the properties of the modified bitumen can be due to an excessive increase in bitumen roughness; in addition to cause premature cracks in bitumen and asphalt mixture, this increase can also reduce the integrity of the modified asphalt mixture (Andrés-Valeri et al., 2018; Bessa et al., 2019; Gupta et al., 2019; Zahedi et al., 2020). However, based on the results of this research and other researches, the use of the appropriate amount of cellulose fibers can improve the properties of the modified bitumen according to the method of preparation and the source of fibers. Various methods of producing cellulose microfibers and nanofibers, like mechanical, physical, and chemical methods, including acidic and alkaline hydrolysis, as well as the availability of different sources for preparing cellulose fibers have caused the characteristics and cost of modifying bitumen and asphalt mixture with these types of fibers to be very different. For example, in the mechanical method, high shearing force and prolongation of the production process can cause damage to the cellulose crystals (Moon et al., 2011), or in the chemical method, due to dissolution in acid, the desired properties of the fibers such as the surface roughness of the fibers decreases. Also, the physical method requires using a lot of energy to produce microfibers (Frone et al., 2011); Therefore, in addition to reduce the production time of cellulose micro fibers and its lower cost compared to other researches, using the waste materials of paper factories has a less negative effect on the properties of the fibers including the surface roughness of the fibers.

Also, unlike polymer bitumen, the samples containing paper pulp have storage stability and therefore there is no need to use other additives to solve the problem of storage stability. According to the results of past researches, the use of lignin can help resist the formation of carbonyl functional groups in the modified bitumen after short-term and long-term aging; therefore, lignin can be used as an antioxidant to reduce the negative effects of aging in bitumen and asphalt mixture.

5. Conclusion

The main purpose of this research was to investigate the possibility of using cheap waste materials from paper factories to improve the mechanical and rheological properties of bitumen. Based on the tests and analysis and evaluations performed, both additives investigated in this research, i.e. cellulose micro fibers and liquor have improved the properties of bitumen at high temperature; however, some limited weaknesses, such as an excessive increase of bitumen stiffness when an increase in the additive percentage, can limit the use of this type of additive to improve the properties of bitumen.

According to the results of the past researches, the use of cellulose fibers has increased the hardness of bitumen in this research too, so that the penetration degree of the modified bitumen has decreased by 10-26%.

Also by reducing the degree of penetration, the softening point of the modified bitumen shows an increase of about 9 to 35% compared to the base bitumen; therefore, with the increase of the penetration index due to the increase of bitumen hardness, the thermal sensitivity of all the modified bitumen has decreased.

Despite the increase in the mixing temperature and compactness of the modified samples, they still did not have much effect on the increase in the mixing temperature and compactness of the bitumen compared to the polymer bitumen of cellulose micro fibers and liquor.

Due to the increase in hardness and as a result of the increase in the rutting parameter in the modified bitumen, all the additives examined in this research have improved the high working temperature of the bitumen; however, despite the improvement of high-temperature performance, the use of large amounts of additives can have a negative effect on other bitumen properties. Also, the data obtained from the creep and return tests at several stress levels and the linear amplitude sweep confirms the results of the SHRP tests with the same trends but at different levels. According to the results of SHRP Plus tests, the use of cellulose micro fibers with an amount of 6% or less can have a significant effect on improving the properties of bitumen. Also, in the combined sample of 6% liquor and 4% cellulose micro fibers, the properties of bitumen, including its fatigue life, have been significantly improved.

Regarding the low-temperature performance of bitumen, due to the increase of the m-value parameter, all the modified bitumen, except the bitumen containing liquor, have performed better at low temperature; however, it has only improved to one grade.

According to the obtained results, liquor has had a negative effect on the low-temperature performance of bitumen due to the increase of bitumen hardness; however, the use of cellulose microfibers has been able to improve the high-temperature performance of bitumen and reduce the negative effect of liquor on the low-temperature performance of bitumen.

In this research, only the effect of cellulose micro fiber additives and liquor on the physical and rheological properties of bitumen has been investigated, so the results of this study cannot be generalized to asphalt mixtures and it is necessary to investigate the effect of using the mentioned additives in asphalt mixtures.

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