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RESEARCH ARTICLE

MULTI-CRITERIA OPTIMIZATION OF PUBLIC TRANSPORT ON DEMAND.

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Abstract

With economic development, we are witnessing a high intensity of road traffic in general and especially public transport in particular. Unfortunately, this situation has negative environmental and economic consequences in the urban environment. To remedy this, several research have been made to optimize this type of transport. In this paper, we propose an optimal public transport management system which minimizes different criteria including travel distance, vehicle service time and safety obstacles (radius of curvature of turns and degree of slopes). The application of our model on different datasets gives better results compared to other works.

Introduction:-

Urban transport has an important influence on the environmental and socio-economic plan of any country. Indeed, from the perspective of sustainable development, good transport management helps to guarantee a healthy environment through a reduction in greenhouse gas emissions as well as better control of the carbon footprint linked to the movement of goods and services. On an economic level, optimizing vehicle movement will make it possible to reduce energy costs linked to the consumption of fossil fuels which are becoming increasingly rare, and which are gradually experiencing price increases that are increasingly untenable for consumers.

According to a World Bank report [1], for example, residents of the Ivorian economic capital (Abidjan) make 10 million trips per day. The loss of time and productivity, associated with the disorder and budgetary cost of daily travel in this economic capital, corresponded to almost 5% of GDP in 2017.

Two main modes of transport are generally practiced in urban areas: public transport consisting of buses, communal taxis, minibuses and also means of lagoon transport; individual transport consisting of individual cars. Despite the environmental problems (traffic jams) and user costs (gasoline prices) that it entails, this last category remains quite widespread in urban areas.

Given its many advantages, improved public transport would be a good alternative to guarantee sustainable development and satisfaction of user expectations in large cities. This improvement makes it possible to guarantee a better quality/cost ratio of service through a compromise between two criteria: the operating cost and the quality of service offered to users. This type of transportation service is generally referred to as on-demand transportation or TAD, and is considered a collective, individualized, on-demand mode of transportation. It combines the advantages of the two main modes of transport mentioned above (public and individual).

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Our work will be structured around four main sections. In the first part, we will approach a description of the state of the art. In the second part we will define the problem then the third part concerns the conceptual study and implementation of our system. The fourth part will be devoted to the discussion of the results obtained. We will end with a conclusion with research perspectives.

State of the art

Most public transit optimization algorithms essentially boil down to optimizing the distance traveled by vehicles. There are plenty of them in the literature. Some consider a single criterion while others are multi-criteria. In this section we present some main academic works on the said subject.

Two founding algorithms are the basis of the different searches for the shortest path in a graph. These are Bellman-Ford's and Dijkstra's.

Bellman and Ford introduced, in [2], one of the first algorithms for solving shortest path problems which is based on dynamic programming [3], the principle of which consists in solving an optimization problem by breaking it down into sub-local problems and resolving them optimally.

The Dijkstra algorithm [4], one of the most widely used shortest path algorithms, makes it possible to construct the tree of shortest paths starting from a source x of the graph towards all other accessible nodes. It is better than the Bellman-Ford algorithm from the point of view of efficiency and algorithmic complexity.

It is important to note that the complexity of public transport optimization algorithms in the literature depends on the number of criteria or objectives considered. Thus, we distinguish in the literature between uni-criterion, bi-criterion and multi-criteria optimization work.

Danchuk et Al. (2017) [5] propose a shortest path optimization solution using the ant colony algorithm. In this algorithm, the shortest path is determined, after exploration and evaluation of each path by a population of subjects. The authors of this article propose a modification of this mathematical model by integrating a dynamic evolution of traffic which allows them to obtain convincing results depending on the traffic conditions. However, the model does not introduce any constraints: circulation can only be considered by changing the valuation of the arcs.

Tomhave and al. (2022) [6] proposed an optimization model that considers user profiles rather than the shortest path. They are based on the assumption that many users often avoid taking the shortest route in terms of distance to get from point A to point B, because of the long waiting times that the latter could cause. Thus, in a first step, the authors determine the shortest path among several interesting paths generated using Dijkstra's algorithm. The latter is then used to calculate other paths by deleting some of the nodes and arcs it uses. After a series of deletion and search of nodes and arcs, the desired number of results is obtained. In the end, the results are filtered to extract duplicates and any paths that are too long compared to the shortest.

Aldaihani and Dessouky (2003) [7], for their part, propose a hybrid model which considers two objectives: minimizing the distance traveled by vehicles and minimizing travel time for users. Their heuristic is based on an insertion-reinsertion phase, followed by tabu search.

Melachinoudis, Ilhan and Min (2007) [8] also proposed a heuristic whose objective is to minimize a linear combination of transport costs and traveler dissatisfaction. They developed an approach based on tabu research which uses the reinsertions of transport requests.

Finally, Zidi and al [9] propose a dynamic multi-criteria solution using the multi-objective simulated annealing algorithm. It combines this algorithm with the management of user profiles to personalize the service offering using a Multi-Agent System.

Objective and Problem:-

Several research works focus on two-criteria problems with the use of exact methods [10] [11] [12] which are effective only for small problems. For multi-criteria problems (more than two criteria) and/or large sizes with higher complexity, there are no efficient exact algorithms that provide a solution in a reasonable time.

Moreover, most of these works do not take traffic constraints into account in their route optimization principle. Indeed, logically, users generally prefer to take routes that are both safe and minimize the number of detours. Thus, a journey may be short in terms of distance but present safety risks due to certain obstacles, including the importance of the radius of curvature of the bends or the high degree of these slopes. This would therefore lead a user to prefer a longer path with fewer obstacles [13] (Akgol et al., 2020).

This choice may be motivated by the time saving it will obtain because the tighter a turn, the more a driver must decelerate to take it, according to an analysis carried out by Khoo et al. (2018) [14].

Finally, unlike certain works in this state of the art, better optimization of the public transport problem requires the satisfaction of several criteria.

The challenge of our work therefore consists of setting up an optimal management system for public transport which minimizes various criteria including the cost of travel, vehicle service time and safety obstacles (angle of turns and degree of slopes).

Methodology:-

Modeling the problem

To solve this transport optimization problem, we propose a model based on a metaheuristic, namely the simulated annealing algorithm following the aggregation approach [15].

In this section we present the mathematical modeling of our proposal as well as the multi-objective simulated annealing algorithm used.

Problem variables:

- $\mathcal{A}$: Set of edges or arcs of the graph$\mathcal{G}$
- n : Number of transport requests
- $\mathcal{D} = \{1, \ldots, n\}$: set of stopping points for users to be transported.
- $\mathscr{F} = \{n + 1, \ldots, 2n\}$: Set of user endpoints
- $\mathcal{S}$: All vehicle parking points (or depots).
- $\mathcal{K}$ =Set of points limiting the edges of the graph$\mathcal{G}$.
- $\mathcal{N} = \mathcal{D} \cup \mathscr{F} \cup \mathcal{S} \cup \mathcal{K}$: Set of all nodes in the graph$\mathcal{G}(\mathcal{N}, \mathcal{A})$
- $\mathcal{V}$: All vehicles intended for user transport.
- Q_v : Vehicle capacity.
- n_{vi} : Number of users taken by vehicle v at station i such that$i \in D$.
- $[t_i\ k_i]$: Time interval associated with departure$i \in D$.
- $[t_{i+n}\ \ k_{i+n}]$: Time interval associated with arrival$i+n \in D$.
- C_v: Cost of vehicle use per kilometer.
- $C_{ijv} = C_{ij} \times C_v$: Transport cost from i to j with vehicle v
- T_{ijv} : Transport time from i to j with the vehicle v.
- t_{siv}: Service start time for request i with vehicle$v$.
- t_{aiv}: Arrival time of request i at destination with vehicle$v$.
- N_{iv}: Number of passengers in vehicle v after visiting point i such that$i \in \mathcal{N}$.
- N_{sv}: Number of passengers in vehicle v leaving a depot
- ξ_{ijv}: Problem decision variable, $\xi_{ijv} = 1$ if the vehicle takes a direct path from i to j, otherwise$\xi_{ijv} = 0$.
- ψ_v = coordinates (x,y,z)of the nodes of the set$\mathcal{N}$
- $\mathscr{L}_{\mathcal{A}}$ = vector indicating the length of the arcs of the set$\mathcal{A}$
- P = slope of the arc taken from i to j
- θ = angle of turn or curvature between two arcs of the path from i to j
- Δ = matrix indicating the Euclidean distance between two nodes of$\mathcal{N}$
- C = current node visited, ($C \in \mathcal{N}$)
- A = penultimate node of the path linking starting point I to C ($A \in \mathcal{N}$)
- B = neighbor node of C not having been visited($B \in \mathcal{N}$).

- The Objective Function:

Our global objective function F is composed of the sum of the transport cost (f_{CT}), service time (f_{TS}) and road safety (f_{SR}).
With:

$$F = f_{CT} + f_{TS} + f_{SR} \quad (E.1)$$

$$f_{CT} = \sum_{i \in D} \sum_{j \in D} \sum_{v \in \mathcal{V}} \xi_{ijv} C_{ijv} \quad (E.2)$$

$$f_{TS} = \sum_{i \in D} \sum_{v \in \mathcal{V}} (t_{aiv} - t_{siv}) \quad (E.3)$$

$$f_{SR} = \text{Slope (P)} + \text{Bend curvature (CV)}^{-1} \quad (E.4)$$

$$\text{Slope (P)} = 100 \times \frac{\psi_v(B,3) - \psi_v(C,3)}{\mathscr{L}_{\mathcal{A}}(CB)} \quad (E.5)$$

The turning curvature (CV) represented by the curvature angle θ (figure 1) is calculated according to Al Kashi's formula, as follows:

$$\theta = \arccos\left(\frac{a^2 + b^2 - c^2}{2ab}\right) \quad (E.6)$$

(E.7)

That's to say:

$$\theta = \arccos\left(\frac{\mathscr{L}_{\mathcal{A}}(AC)^2 + \mathscr{L}_{\mathcal{A}}(CB)^2 - \Delta(A,B)^2}{2\mathscr{L}_{\mathcal{A}}(AC) \times \mathscr{L}_{\mathcal{A}}(CB)}\right)$$

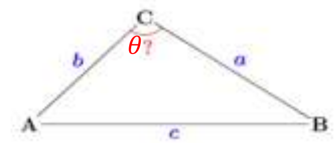

Figure 1: Bend angle θ

So :

$$f_{SR} = \sum_{B \in \mathcal{N}} \sum_{C \in \mathcal{N}} \left[100 \times \frac{\psi_v(B,3) - \psi_v(C,3)}{\mathscr{L}_{\mathcal{A}}(CB)} + \arccos^{-1}\left(\frac{\mathscr{L}_{\mathcal{A}}(AC)^2 + \mathscr{L}_{\mathcal{A}}(CB)^2 - \Delta(A,B)^2}{2\mathscr{L}_{\mathcal{A}}(AC) \times \mathscr{L}_{\mathcal{A}}(CB)}\right)\right] \quad (E.8)$$

Where

$$\Delta(A,B) = \sqrt{\left(\psi_v(B,1) - \psi_v(A,1)\right)^2 + \left(\psi_v(B,2) - \psi_v(A,2)\right)^2} \quad (E.9)$$

Therefore, the overall objective function is :

$$F = \sum_{i \in D} \sum_{j \in D} \sum_{v \in \mathcal{V}} \xi_{ijv} C_{ijv} + \sum_{i \in D} \sum_{v \in \mathcal{V}} (t_{aiv} - t_{siv}) + \sum_{B \in \mathcal{N}} \sum_{C \in \mathcal{N}} \left[100 \times \frac{\psi_v(B,3) - \psi_v(C,3)}{\mathscr{L}_{\mathcal{A}}(CB)} + \arccos^{-1}\left(\frac{\mathscr{L}_{\mathcal{A}}(AC)^2 + \mathscr{L}_{\mathcal{A}}(CB)^2 - \Delta(A,B)^2}{2\mathscr{L}_{\mathcal{A}}(AC) \times \mathscr{L}_{\mathcal{A}}(CB)}\right)\right] \quad (E.10)$$

- Our mathematical model:

The modeling of the problem consists in minimizing the objective function F, under different constraints that we will specify in this section.

$$\begin{cases} \text{Min } F(\xi_{ijv}) \\ \text{s.c } X \in C \end{cases} \quad (E.11)$$

- Any vehicle v arriving at a node i leaves it:

(E.12)

- A vehicle v starts the service in j only after having finished the service in i and taken the arc(i, j) : (E.13)

- In order to carry out the boarding service on time, each vehicle v must respect the request time interval at a departure nodei: (E.14)
- In order to provide the service on time, each vehicle must respect the arrival time interval at an arrival nodei+n : (E.15)
- The number of users in a vehicle v after leaving a departure node i is greater than that collected at i and less than the maximum capacity of the vehicle: (E.16)
- The number of users in a vehicle v after visiting a node i+n is greater than or equal to the capacity of the vehicle minus the number of users included in the transport requesti: (E.17)
- When departing from a depot, each vehicle has no passengers (E.18)

Operating principle of the simulated annealing algorithm:

This algorithm was inspired by the process of physical annealing from statistical mechanics. It consists of finding lower cost configurations through an iterative procedure. In other words, the algorithm makes it possible to iteratively find a minima (global optimum) in a neighborhood of a given initial solution. To do this, it partially explores the set of possible solutions starting from a random initial solution to which a modification is applied to obtain a new solution. If the cost of this new solution is better than that of the previous solution, we retain the new solution and repeat the process until no modification produces a better solution [16].

The pseudo-code of the RS algorithm is as follows:

Algorithm 1: Pseudo-code of the Simulated Annealing algorithm
1. Choose an initial solution s_0 (randomly or according to a heuristic) 2. Initialize temperature $T = T_{max}$ 3. As long as ($T > T_{min}$) Do : 3.a. Find a solution s_j close to s_0 3.b. Calculate $\Delta F = F(s_j) - F(s_0)$ 3.b.1. If $\Delta F < 0$ 3.b.2. $s_0 = s_j$ (Replaces_0 by s_j) 3.c. Else 3.c.1. Randomly choose a real number $\zeta \in [0,1]$ 3.c.2. If ($\zeta < e^{-\Delta F / T}$), then $s_0 = s_j$ (Replaces_0 by s_j) 3.c.3. End If 3.d. End Else 3.e. Calculate T such us $T = T \times \mu$ 4. End As long as.

To solve our public transport optimization problem, using the simulated annealing algorithm, it is important, after the Objective Function, to define a method for generating the initial solution "s_0" as well as a method of searching for the neighborhood “V(s)”.

The following figure (figure 2) models our system for searching for the global optimal solution.

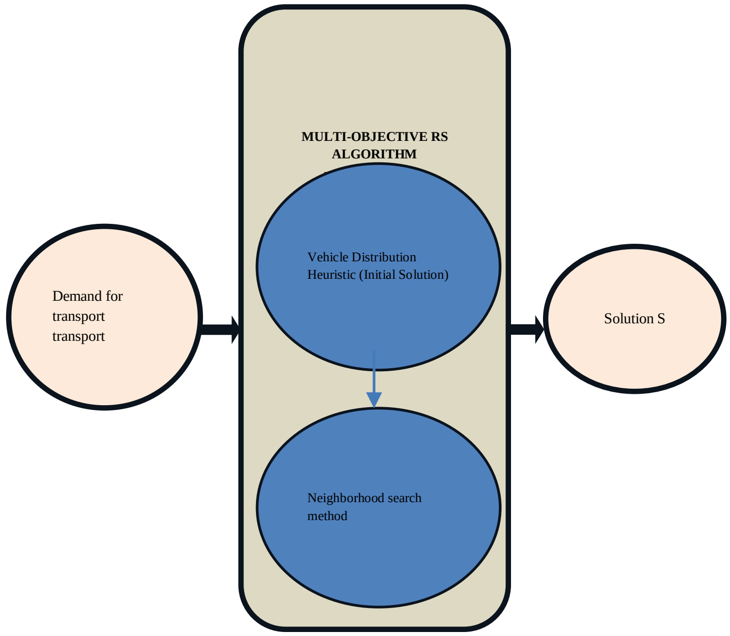

Figure 2:-Optimal solution search system.

Choice of initial solution s_0

For our work, we used a constructive heuristic based on an iterative local search for the selection of our initial solution. We choose beforehand in all the road, a roadstarting from the vehicle depot. From the list of transport requests from waiting users, we iteratively select the request with the lowest transport costC_{ijv} and we add it to the route while respecting the capacity constraintQ_v of the vehicle. Each request is defined with the user's departure point and arrival point.

The pseudo-code of the algorithm for choosing the initial solution is as follows:

Algorithm 2: Selection of the initial solution
1. Define set $\mathcal{A}$of road (or arcs) and set $\mathcal{D}$of transport requests. 2. For any item d ∈ $\mathcal{D}$and ∀r ∈ $\mathcal{A}$, Do 2.1. As long as the number of passengers N_{sv} in the vehicle is less than itscapacity Q_v 2.1.1. Randomly choose a road r starting from vehicle depot V 2.1.2. Order transport requests in descending order according to trip cost C_{ijv} 2.1.3. Add request to selected road. 2.2. End As long as 3. End for

Neighborhood search

The objective being to obtain a better global solution, modifications must be applied to the current solution through a neighborhood search method. For our work, we use a neighborhood exchange method. It consists in randomly exchanging two neighboring nodes (passengers) of a road r1 by two other adjacent nodes of another road r2, by evaluating for each exchange, the cost incurred.

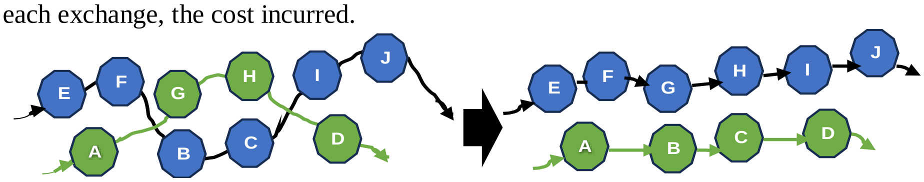

Figure 3:- Neighborhood structure by node insertion.

In our example, if we note by:
$\mathcal{A}_{r1}$, the set of arcs that make up the road r1={EF, FB, BC, CI, IJ}
$\mathcal{A}_{r1}$, all the arcs which constitute the road r2={AG, GH, HD}
C_{r1}, the cost of the road $r_1$before the exchange, $C_{r1} = \sum_{x \in \mathcal{A}_{r1}} C(x)$ (E.19)
C_{r2}, the cost of the road $r_2$before the exchange, $C_{r2} = \sum_{x \in \mathcal{A}_{r2}} C(x)$ (E.20)
The cost (C_{BC-GH}) of exchanging adjacent nodes (or passengers) B and C of road r1 by neighboring nodes G and H of roadr2 is obtained as follows:
$C_{BC-GH} = C_{BC} + C_{GH}$, (E.21)

Where
$C_{BC} = C_{AB} + C_{BC} + C_{CD} - C_{r2}$ (E.22)

$C_{GH} = C_{EF} + C_{FG} + C_{GH} + C_{HI} + C_{IJ} - C_{r1}$ (E.23)

The pseudo-code is as follows:

Algorithm 3: Neighborhood search
Define two road (or arcs) r_1 and r_2 and a set of nodes (respective passengers) belonging to each road. 1. Randomly select 2 nodes on each route $r_1$and r_2 2. Calculate the costs of the arcs making up each road. 3. Calculate the costs C_{ech} caused by the exchange. 4. If $C_{ech} < 0$, do exchange of nodes.

Experimentation and evaluation

Experimental framework

For our experiment, we used data from the benchmark of (Cordeau and Laporte, 2003) [17]. The latter includes 20 instances containing problems of varying sizes ranging from 24 to 144 transport requests. Also, 3 to 13 homogeneous vehicles are used to serve these requests. We have also supplemented this data with some simulated data relating to arcs and nodes on the roads, in order to facilitate the calculation of the slopes and angles of curvature of the bends.

In this section, we will compare our results to those obtained by (Zidiand al, 2010) using the same experimental data. The test was carried out with four instances of the benchmark cited above, namely the R1a instances (24 requests and 3 vehicles), R5a (120 requests and 11 vehicles), R1b (144 requests and 13 vehicles) et R4b (108 requests and 8 vehicles).

Results:-

Tests were performed using the simulated annealing algorithm parameter values recorded in the table below. We retained these values after numerous tests on the instances used.

Table 1:- Parameters of the Simulated Annealing algorithm.

Parameters	Value
T initial = $\mathbf{T_{max}}$	3250
T final = $\mathbf{T_{min}}$	0,0015
$\boldsymbol{\mu}$	0,97
Number ofiteration	760

The following table 2 presents the results obtained through our approach and that of Zidi.

Table 2:- Results obtained using our approach and that of Zidiand al.

Instances	Distance traveld		Travel time (min)		Execution Time (min)	
	Coulibaly and al	Zidiand al	Coulibaly and al	Zidiand al	Coulibaly and al	Zidiand al
R1a	267,31	260,85	906,84	982,06	0,34	0,18
R5a	998,66	989,56	3418,05	3537,2	0,82	0,29
R1b	309,1	308,89	942,23	877,62	0,21	0,24
R5b	1017,04	1006,52	2694,1	2947,4	0,9	0,28
Totale	**2592,11**	**2565,82**	**7961,22**	**8344,3**	**2,27**	**0,99**

In Figure 4 below, we present a comparative graph of the results obtained using our approach and that of Zidiand al.

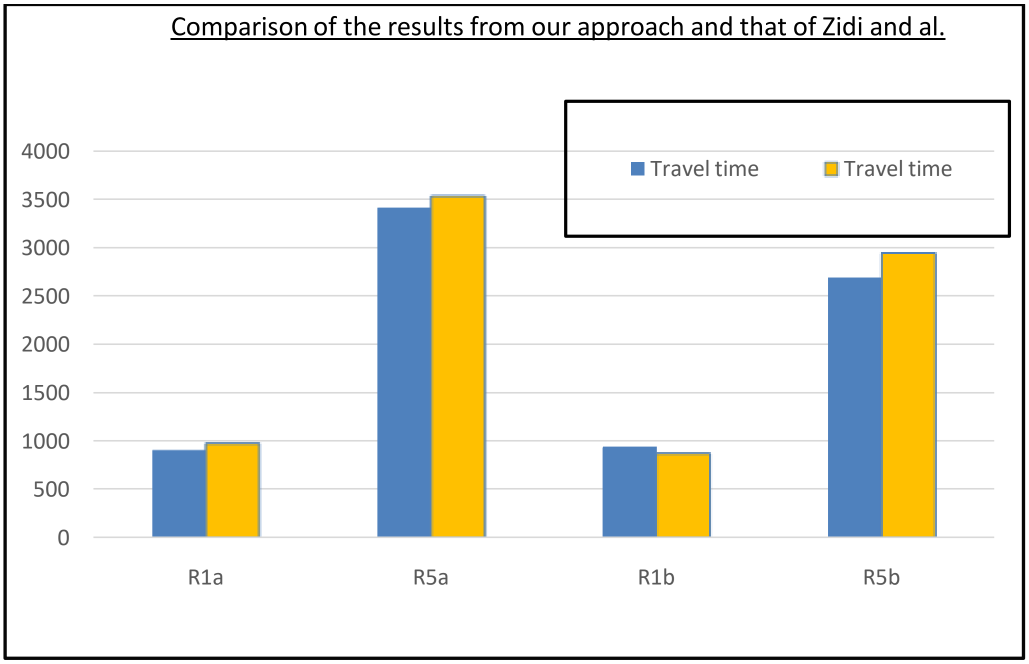

Figure 4:- Comparison of our results with those of Zidiand al.

Discussions:-

The analysis of the results presented in the previous section (figure 4) shows the effectiveness of our approach at the level of instances R1a, R5a and R5b compared to that of Zidiand al. But for the R1b instance, Zidi's approach is better than ours.

We also observe, in Table 2, that for the same instances (R1a, R5a and R5b), with our approach, the distances traveled by the vehicles are greater than those traveled using the Zidi approach. Likewise, the time taken to cover these distances is smaller in our case.

This is explained by the fact that with our approach, the algorithm does not favor the distance of the journey in terms of length buttakes into account the traffic constraints (slope and turning angle) which in practice increase the time of travels. With our approach, a vehicle will therefore take a long route with fewer turns and slopes compared to a short route with more turns and slopes.

The effectiveness of Zidi's approach at the level of the R1b instance can be explained by the fact that there are fewer obstacles on the route concerned.

Ultimately, our approach shows better results than those of Zidi for instances including routes with significant slopes and turning angles.

Our approach was executed on a MacBook Pro laptop with 3.1 GHz Intel Core i7 quad-core processor with 16 GB 2133 MHz RAM.We used the Python language for the implementation of our approach.

Zidi and al's approach was tested using a Dell B14DEE640C laptop containing an Intel Core 2 Duo 2Ghz processor and 2GB RAM. The JAVA language was used for the implementation.

Conclusion and Future Work:-

Our present work is part of the context of improving public transport to offer transport companies and users quality services that are safe, economical and ecological. The objective was therefore to propose an approach that determines the shortest path by considering certain constraints impacting the safety and the duration of the transport: the angles of turn and the slopes on the roads.

After analyzing the main works in the literature on the problem of public transport, we modeled our approach. Our mathematical model considers the minimization of several criteria including travel cost, vehicle service time and safety obstacles (angle of turns and degree of slopes).

We then used a metaheuristic, in this case the Simulated Annealing algorithm following an aggregation approach, to solve our transport optimization problem. This allowed us to obtain better results compared to the approaches proposed in the literature.

For the validation of our approach, we used benchmark data from (Cordeau and Laporte, 2003) [17]. as well as some random data on the aspect of the roads in terms of slopes and curvatures of the turns.

The prospects for our work lie in the improvement of the algorithm used as well as in the experimental data. Indeed, to allow a good exploration of the search space as well as the reduction of the calculation time, a hybridization of the RS algorithm used here with another metaheuristic such as tabu search, will be a good prospect. Concerning the data, it would be interesting to use real data, particularly on the road network with measurements on slopes and turning angles.

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