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A Macroscopic Fundamental Diagram for Spatial Analysis of Traffic Flow: A Case Study of Nyeri Town, Kenya

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Abstract: Traffic flow analysis is an essential component of a town's traffic and transport systems since these flows could, and often do lead to the occurrence of congestion on our roads. Traffic congestion is a growing problem in Nyeri, Kenya, resulting from rapidly increasing population and the crowding of motorized traffic onto a limited street network. This research performed spatial analysis of traffic flows on some road links in Nyeri town. On those selected road links it also established fundamental traffic flow models and derived the flow characteristics associated with traffic operations in Nyeri town, determined the characteristics of a Macroscopic Fundamental Diagram (MFD) for Nyeri town and assessed to determine whether it is a property of the network infrastructure and control or of the travel demand. In this research, MetroCount Vehicle Classifier was used to collect traffic intensity and velocity data at different locations of the network over certain durations and at the same period between January 2015 and February 2015. The analysis of the data was performed by the MetroCount Traffic Executive MCReport. The MFD resulting from the study served as a road network performance indicator, which tells the performance levels of the town in general, in terms of traffic flow. The research was used to determine the capacity of the road network and the level of congestion in different links thereby determining the adequacy of the network. The speeds in Nyeri town are moderate, however, low and high speeds occur occasionally and the volumes of traffic in Nyeri town are not high hence congestions are rarely experienced. The results of this research study are anticipated to better traffic management, and also improve mobility and accessibility in Nyeri town.

Keywords: Microscopic Fundamental Diagram, Network Infrastructure, Nyeri Town, Spatial Analysis, Traffic Flow

1. Introduction

Traffic flow analysis is an essential component of a town's traffic and transport systems since these flows could, and often do, lead to the occurrence of congestion on our roads [1]. Global cities and towns face rising traffic congestion problems. This situation is getting worse and is becoming a major concern of the general public. Traffic congestion is a condition of traffic delay, because the number of vehicles using a road exceeds the operational capacity of the network to handle it [2]. Congestion has several causes such as: the volume of traffic being close to the maximum capacity of the road link and as a result of too many vehicles crowding available road space. Congestion has a number of negative effects: productive hours are lost and this has adverse effects on the economy; it also contributes to air pollution (which has a debilitating effect on quality of life) and global warming. In view of these effects of congestion, there is the need to manage traffic congestion and help reduce its effects.

Congestion occurs on individual links within a network thereby making it a localised problem. The cause has to do with spatial - temporal distribution of demand and supply which therefore makes it possible to experience its effect when considering the performance of the entire network, making it a macroscopic issue. This then points out at the fact that network operators should be able to relate the effects of these localised congestion situations on road links to the entire network, which calls for appropriate indicators to be used to measure network performance [2]. Analysis of traffic flow and modeling of vehicular congestion has mainly relied on fundamental laws, inspired from physics using analogies

with fluid mechanics, many particles systems and the like.

Nyeri town was initially the administrative headquarters of the country's former Central Province. Following the dissolution of the former provinces by Kenya's new constitution in 2010, Nyeri is now the largest town in the newly created Nyeri County, with a population of about 119, 273 (National Bureau of Statistics, 2009). Modern shopping centres and department stores that were found in much larger cities and towns have been opened in Nyeri as a result of the booming economic activities. Nyeri is served by a reasonably well - maintained tarmac road network connecting it to Nairobi, Nakuru, Nanyuki, Othaya and other surrounding towns. Most transportation of cargo to and from Nyeri is by road. The main mode of public passenger transport to, from, and within Nyeri is by way of fourteen - seater minibus taxis (matatus), though un - metered saloon car taxis are also widely used. The above - stated increase in population, business and economic activities also has effects on traffic flow in the town.

2. Statement of the Problem

In Nyeri town, despite the intensive road network expansion and the limited number of vehicle ownership compared to the other sub Saharan countries, traffic congestion has now become the threat in the town economic growth by restraining the commuters' mobility especially at peak hours. In addition to waiting time for the limited public transportation, both vehicle owners and public transport users are forced to delay within the congested traffic lane. Hence, late arrival to work places and appointments for social or business activities have become common. Despite the problem being recognized by all road users and transport professionals, there is no significant attempt for quantitative research done on the extent of the traffic flow and congestion in Nyeri. Traffic congestion has an economic cost on the productivity of the town's communities and economy. Primarily, traffic congestion is an outcome of insufficient traffic management in the town, insufficient capacity of the roads to cope up with the existing traffic volume and inadequate public transport, fixed working time, and poor land - use or transport - land - use planning integration. In addition, long travel time or delay to reach destination, affect business users' time productivity and increasing fuel consumption and wastage. These are the main impacts of vehicles congestion which are prevalent. Therefore, this research has been initiated to assess traffic congestion and the impact of the issue on travel time and fuel consumption.

3. Study Objective

To determine the characteristics of a Macroscopic Fundamental Diagram (MFD) for Nyeri town

4. Theoretical Framework

4.1. Traffic Flow Theory

Transportation, which is seen as a system that considers the complex relationships between its core elements such as networks, nodes and demand, plays an essential role in our daily lives [3]. This relation gives rise to the flow of traffic on road networks. The mathematical representation of the interactions between vehicles, their operators and the infrastructure can be explained by traffic flow theories which seek to understand and develop optimal road networks that will allow the movement of traffic efficiently and help reduce congestion [4]. Road space is limited and traffic engineers have to maximise the capacity of the road as much as possible. The measurement of the capacity and what influences it, lie at the core of traffic flow theory [5]

It is asserted that the sole aim of transportation is to meet demand levels for mobility [3]. In this regard, travel demand modelling is viewed as an important factor in transport planning processes in that demand levels could directly be as a result of the outcome of varied economic activities, without which they would not occur; so there is the need to be able to predict demand levels so as to plan towards their effects.

Although traffic flow plays these requisite roles, their negative effects on the environment is one that should be well considered. An indirect effect of congestion caused by transportation is pollution (air and water); and this affects health standards of people. Also to talk about is its safety issues because growing traffic is linked to growing number of fatalities and accidents. With respect to its environmental effects, it is emphasized that" decisions relating to transport need to be evaluated taking into account the corresponding environmental costs" [3]. Other cost considerations which have effects on economies can also be seen from the delays spent in congestion and although transportation may have these negative effects, it plays very essential roles by supporting transport demands that are generated by the diversity of activities that are brought forth by the urban society.

4.2. The Fundamental Diagram Model

How effective a roadway system is can be evaluated based on a number of elements which include the number of vehicles that can travel on the road, the speeds at which these vehicles can travel, the density of vehicles along the roadway, the distances between these vehicles and the freedom to manoeuvre among lanes. These qualitative and quantitative measures affect each other in one way or the other and the derivation of the macroscopic parameters which relate to form the MFD have been shown below.

When vehicles move in a traffic stream, a relationship exists between spacing *(s)* and the density *(k)* of the stream of vehicles on a given length of a roadway. This is given by:

$$s = \frac{1}{k} \qquad (1)$$

Also, the headway *(h)* between these vehicles in a stream is the inverse of traffic flow *(q),* thus:

$$h = \frac{1}{q} \qquad (2)$$

And the headway *(h)* between two vehicles travelling at a spacing *(s)* with a speed *(u)* is given by:

$$h=\frac{s}{u} \qquad (3)$$

Substituting equations 4.21 and 4.22 into 4.23 gives the relation between the macroscopic variables flow, speed and density as:

$$q=uk \qquad (4)$$

This equation represents the behaviour of one parameter with respect to the other and is the basis for the fundamental diagram since it involves a relation between traffic flow, traffic speed and traffic density. The sections below show how each of these parameters relate to the other and what kind of information can be obtained from them. As part of this research, the application of data from metro count devices was analysed to give rise to the MFD. Based on the interpretation from the diagram, information obtained from it can be used by planners and traffic engineers to further plan traffic circulation within a study area such as Nyeri town.

5. Empirical Review

5.1. Network Reliability

How reliable the road networks are, is becoming an increasingly important attribute of road networks and also a concern for planners and engineers in network design [6, 7]. This is because a network that is unreliable has effects on the lives of commuters and the economy of the nations, giving concern to studying the reliability of networks during area - wide studies. Reliability is defined from systems engineering point of view, as the degree of stability of the quality of service that a system normally offers; and in a transport system such as a road network, travel demand flows and the physical network may contribute to how reliable the network is. A similar idea is asserted that" reliability, by its nature, implies something about the certainty or stability of travel time of any particular trip under repetition".

In road network reliability [7, 8] share similar views that the level of stability of the transport network system can be related to its ability to respond and meet the expected demand levels under different circumstances (such as variability in flows and physical network capacities). A typical example where a network is reliable is where the network is able to cope with variations in demand over different days of a week by maintaining a constant average travel time between different origin - destination pairs [9].

The focus of this research is to determine factors that will ensure that the road network in Nyeri improves accessibility and mobility levels, thus reducing travel times and improving on its reliability, and that is what transport planners and engineers seek to do. Before improvements are made to the current network structure in terms of planning and engineering, network indicators will have to be used to assess present performance of the network.

5.2. Macroscopic Fundamental Diagram (MFD)

Macroscopic models common to traffic - related simulations have a long history, with the study of fundamental diagrams [10, 11]. The measurements and relationships that exist between macroscopic variables (speed, density and flow) have been broadly studied [12] for traffic streams theoretically and practically [13, 14]. Further works dealt with the development of macroscopic models for arterials [15, 16] and were later extended to general networks [18].

Further experimental findings show that MFDs can be used to control demand and improve mobility and accessibility within a city [19]. This improvement is seen to enhance the performance of the road network and show how the system responds to increasing travel demand levels. Once the MFD for a city is established and mechanisms are put in place to monitor the state of traffic flow, it is possible to know if the network is producing the desired accessibility levels at all times. Since the performance could be attributed to the way a city is planned, a typical MFD for a city/town may help explain if the city/town is well planned or not, or if some selected sections (of spatial interest) are performing better than others so as to know how to allocate resources for transport network improvements in an equitable manner.

Typically, an MFD can be put into four phases (A, B, C, D) as shown in Figure 1 and each of these phases shows the different state of the network with increasing traffic flow.
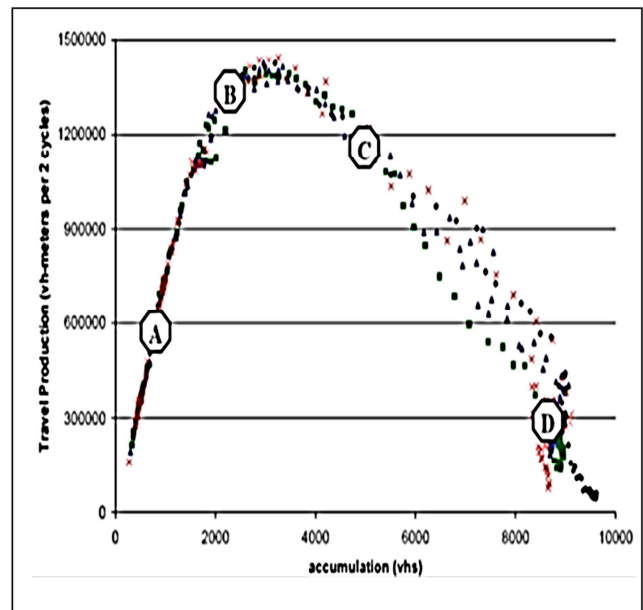

Figure 1. *A Typical MFD for the City of San Francisco [19]*

For the above diagram In Figure 2 - 5, phase A shows the condition when the system is under saturation and the average speed is about 25km/hr with an accumulation of about 952 vehicles. As demand increases the system moves to state B where the vehicle - miles travelled is near the maximum and the average speed is 17km/hr with an accumulation of 2143 vehicles. At this stage, engineers can

tell at what accumulation the system experiences its maximum capacity, and this can be useful for planning purposes as well as knowing the land use activities that contribute to that accumulation. In phase C congestion is broad, long queues are observed and the average speed drops to 7km/hr (with an accumulation of 5337 vehicles). In state D the output is near to zero (at jam density), and the majority of vehicles are stopped (with accumulation of 8943 vehicles). Once again, knowledge about the jam density could assist in putting in management measures to manage the density within the town from getting to such high levels, thereby reducing congestion.

6. Conceptual Framework

The study was guided by a conceptual framework as shown in Figure 2 relating the dependent and independent variables.
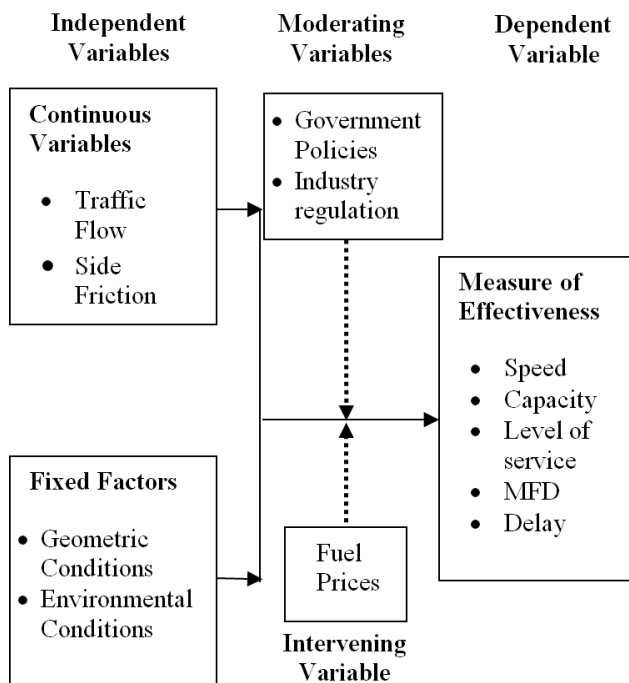

Figure 2. Conceptual Framework.

The independent variables constitute two sets of factors namely continuous and fixed factors. Continuous factors are traffic flow and side friction whereas fixed factors comprise of geometric conditions and environmental conditions. On the other hand, measure of effectiveness was presumed to be in terms of speed, capacity, level of service, MFD, and delay. The study hypothesized that both continuous and fixed factors do affect measures of effectiveness. More so, the study factored in moderating variables which included government policies and transport industry regulations.

7. Research Methodology

This section outlines the types of data, how they were collected. It also presents the instruments adopted in data collection and how the collected data was analyzed. The approach to establishing an area - based indicator for Nyeri town was based primarily on the relationship between average traffic flow and speed for the entire network. The data for this relation was collected by Metro Count Vehicular Classifier over a period of time. Developing very effective strategies to enhance traffic flow conditions on road networks require knowledge on the state of road at any point in time and space. This data was prepared and analysed in different ways to obtain the desired variables/ parameters that needed to be compared; for explanations, conclusions and recommendations to be made. The relationship between average traffic flow and speed for the network was an area of focus since this establishes the MFD, which was used to comment on the performance of the city's road network. Figure 3 outlines the methodological framework for analyzing the collected data.

8. Findings and Discussions

8.1. Introduction

Nyeri town is linked to other surrounding towns by several arterial roads and numerous collector roads that connect to the arterial roads. Data for this project was collected on the seven major arterial roads around Nyeri town. Table 1 shows the major links around Nyeri town

Table 1. Major Arterial Roads (Links) around Nyeri Town.

Link	Length (Km)	No. of travel lanes	Functionality class
Nyeri-King'ong'o	2	2	B5
Nyeri-Kiganjo	9.4	2	C75
Nyeri-Nyahururu	100.2	2	B5
Nyeri-Tetu	6	2	D434
Nyeri-Ruring'u	3.0	2	B5
Ruring'u-Marua	6.0	2	B5
Ruring'u-Othaya	30	2	C70

8.2. Traffic Flow Data

Figure 3 illustrates the average volume of traffic flow within Nyeri town.

Traffic data collected over a two week period for all the roads was averaged to obtain data for a virtual week and then a virtual day as shown in Figure 3. Analysis of the volume

data gave rise to the average volume graph of the town. The analysis of traffic flow for all the roads indicates that the morning peak occurs between 0800hrs and 0900hrs whilst the afternoon peak volume occurs between 1700hrs and 1800hrs. Afternoon peak periods recorded slightly higher volume than the morning peak periods. Nyeri - King'ong'o road recorded the highest traffic volume, that is, more than 1200v/hr.
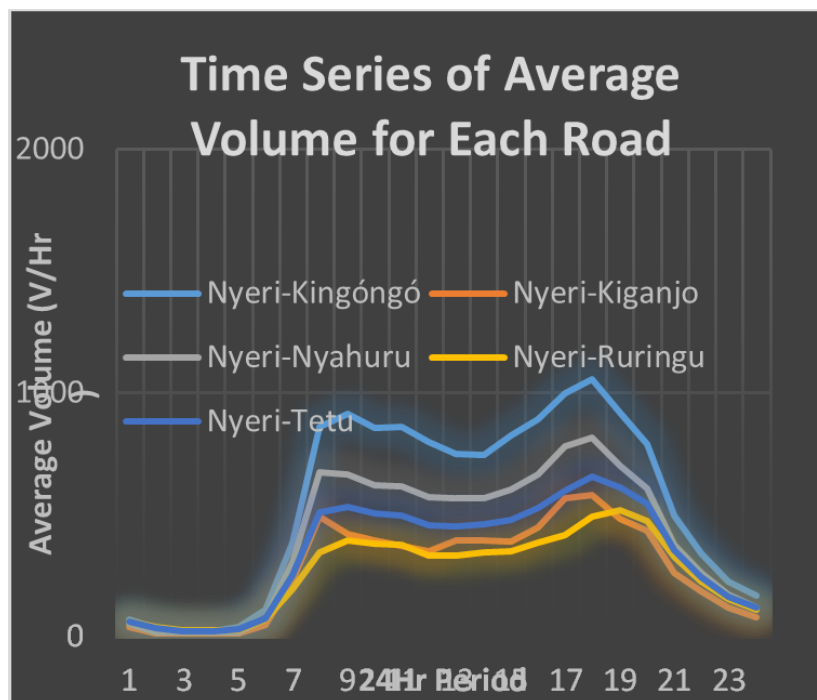
Figure 3. *Average Volume Graph.*

8.3. Speed Data

A time series analysis of speed was performed on all the links and the results of the analysis are as shown in Figure 4.
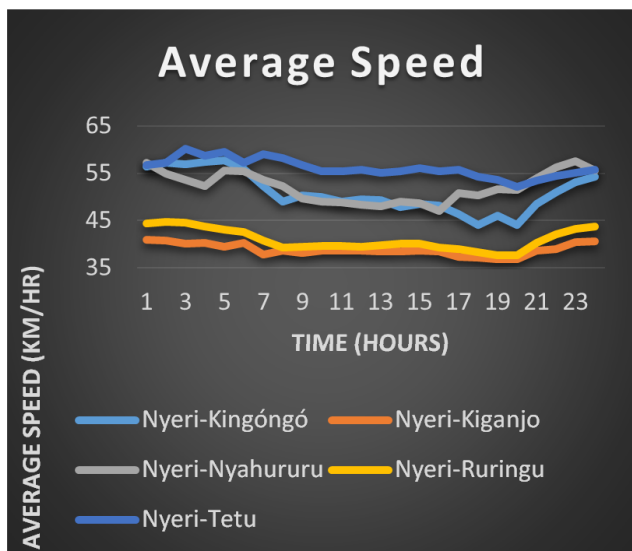

Figure 4. *Average Speed Graph.*

The average speed for the links was found to be 48km/hr. The highest speeds were recorded between 0300hrs and 0400hrs and 2200hrs and 2400hrs. These speed correspond with the times when traffic volume is the lowest hence there is little vehicle interactions. Speed in all the links decreases gradually from 0600hrs until 2000hrs when the lowest speed in the network is reached. The speed graph shows that morning peak periods are 0700hrs to 0800hrs and evening peaks occur between 1700hrs and 1800hrs just as the volume graph indicated. There was a clear repeatability of hourly variations on all roads. Vehicle volume was below 200v/hr before 0600hrs and then increased steadily up to 0800hrs. Volume varied slightly between 0900 hrs and 1900 hrs after which it decreased steadily.

8.4. Macroscopic Fundamental Diagrams

The traffic volume data collected and speed data were used to generate the Fundamental diagrams using Metro Count Executive Report software. The MFDs for each road link were first formulated then the general MFDs for the whole town. The diagrams aided in the qualitative and quantitative analysis of the entire road network.

8.4.1. Speed - Density Model

Vital road network characteristics like free flow speed, critical speed and jam density were obtained from the speed - density model. However, in this research study the speed - density model was used to obtain the free flow speed and critical speed. Table 2 shows the free flow speed and critical speed from the speed - density model.

Table 2. *Free Flow Speed and Critical Speed for all Road.*

Road	Free Flow Speed	Critical Speed
Nyeri-King'ong'o	75	55
Nyeri-Nyahururu	70	50
Nyeri-Kiganjo	55	40
Nyeri-Ruringu	60	40
Nyeri-Tetu	50	55
Ruringu-Othaya	75	40
Ruringu-Marua	55	55

Table 3. Maximum Volume for Each Road Link.

Road	Free Flow Speed (U0)	Critical Speed (Uc)	Max Vol. (qmax)
Nyeri-King'ong'o	75	55	2500
Nyeri-Nyahururu	70	50	600
Nyeri-Kiganjo	55	40	1400
Nyeri-Ruringu	60	40	1800
Nyeri-Tetu	50	55	900
Ruringu-Othaya	75	40	1500
Ruringu-Marua	55	55	1750

Table 4. Jam Density for the Links.

Road	Free Flow Speed (U0)	Critical Speed (Uc)	Max Vol (qmax)	Jam Density (Kmax)
Nyeri-King'ong'o	75	55	2000	40
Nyeri-Nyahururu	70	50	600	20
Nyeri-Kiganjo	55	40	1400	25
Nyeri-Ruringu	60	40	1800	25
Nyeri-Tetu	50	55	900	20
Ruringu-Othaya	75	40	1500	30
Ruringu-Marua	65	55	1750	25

8.4.2. Speed - Volume Model

The speed - volume model in this study was used mainly to obtain the critical volume (maximum volume) and to re - examine the critical speed and free flow speed values. The data obtained from the models are presented in Table 3.

8.4.3. Density - Volume Model

The density - speed volume for the roads (the jam density) was obtained from this model and the speed - density model. Table 4 shows the major characteristics of density - volume model.

9. Conclusions

It has been indicated that the MFD can be used to improve accessibility within towns. Information from the MFD can be channelled into enhancing accessibility levels to ensure effective traffic circulation within the town. This can generally be done with road pricing, rationing and/or perimeter control strategies based on neighbourhood accumulation and speeds, such as those proposed in previous studies [17, 19]. It was concluded that Nyeri town may not be congested enough to be given such measures but these can be thought of and applied where necessary in future instances.

Traffic volumes within the morning and evening peak periods were found to be of great interest to traffic engineers and planners in design and operational analysis since roads to carry traffic are designed adequately to meet such demand levels. These periods exhibit highest traffic volumes and lower speed levels throughout the 24 - hour period. Generally, these periods are estimated considering the work - trip patterns within a town. The analysis with the data suggested that the morning and evening peak periods for Nyeri town are 0800 hours - 0900 hours and 1700 hours - 1800 hours respectively. These periods were first established as a basis for all other analysis. Generally, the evening peaks tend to show a slightly higher volume and a slightly reduced speed levels as compared to the morning peaks. It can further be investigated as to which land use activities within those corridors contribute to this variation. Such studies could enhance the effective distribution of resources in the town.

The study inferred that some road links indeed performed better than others and this is very significant to planners and engineers to further plan traffic flow within the town. All the considered links relatively performed worse between and during morning and evening peak periods. Performance levels were very good ($\approx 100\%$) from 2300 hours till 0530 hours the following day. The research also demonstrated the existence of a macroscopic fundamental diagram for Nyeri town. It was deduced that speed and traffic volumes are related. Nyeri town demonstrated a very high level of correlation between speed and volume and a model was established for the town to demonstrate the same. The model characterises the traffic flow in the town and may not be applicable to other cities as a result of possible different town and network structures. The strong relation also gave an indication that although other factors may contribute to speed variations on the network, traffic volumes accounted for the greatest percentage of variation of speed on the town's network.

Recommendations

It is recommended that further studies should be carried out into the other days where traffic variations for these days could be determined and further explored. For instance, traffic variations could be studied between weekdays and weekends so that traffic circulation within the town would be well understood and appropriate steps put in place to enhance traffic flow. It is further recommended that the designed capacities of the road segments be provided so that further analyses that pertain to comparing the performance levels of different links can be undertaken. In addition, it is suggested

that the study could be replicated in other towns in Kenya in order to establish how a town's network structure (land use and transport planning) affects its MFD.

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