# GEOMETRIC INFORMATION FROM SINGLE UNCALIBRATED IMAGES OF ROADS

L. Grammatikopoulos [a], G.E. Karras [a], E. Petsa [b]

[a] Department of Surveying, National Technical University of Athens, GR-15780 Athens, Greece (gkarras@central.ntua.gr)
[b] Department of Surveying, Technological Educational Institute of Athens, GR-12210 Athens, Greece (petsa@teiath.gr)

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**ABSTRACT**

Video sequences of road and traffic scenes are now used for various purposes. The framework of this research on the metric potential of single uncalibrated images is road mapping and studies of the traffic character of freeways. In the first case, an approach has been developed to extract lane width in straight road segments exploiting sequences from a forward looking camera. Apart from an initial reference width, necessary for calibrating camera height, no intrinsic or extrinsic calibration is required if frontal image acquisition is assumed. This approach, making use of the vanishing point of the road, gave an accuracy better than 5 cm in lane width. The second technique regards the measurement of vehicle speed, given the time interval between frames of a stationary camera tilted downwards. Here, too, the vanishing point in the direction of the road is used, with the vanishing point of the orthogonal direction assumed at infinity. Given one known ground distance along the road axis, the projective distortion of the ground plane is removed, allowing an affine rectification and, thus, 1D measurement in the correctly scaled road direction. This approach, evaluated against rigorous 2D-2D projective transformation and GPS measurements, has given a satisfactory estimated accuracy in vehicle speed of about 3 km/h.

## 1. INTRODUCTION

Video sequences of roads are increasingly used in various contexts. For instance, preserving road network operability is today a basic consideration, mainly focusing on road safety. Road recording and mapping systems are needed to provide the missing data, chiefly as regards older roads constructed and maintained under various jurisdictions. Indeed, several mobile mapping and video-logging systems have been reported (Tao and El-Sheimy, 2000). The former integrate multiple sensors with one, or more, cameras providing geo-referenced image sequences and are capable for precise 3D measurement. Video-logging systems, on the other hand, are typically based on a single camera. Hence no 3D measurement is generally possible in these cases, unless certain geometric constraints are adopted (Tao, 2001). Most important among them is the ‘flat-earth’ model.

The potential of automatic single-image approaches, relying on different geometric assumptions, is being currently investigated in the computer vision literature for various purposes. Probably the main task here is the development of driver-assistance tools or even autonomous road following. In this context, algorithms have been presented for automatic lane and obstacle detection (Bertozzi & Broggi, 1997, Enkelmann, 2001), the estimation of lane shape and a vehicle’s road position or ‘ego-motion’ (Stein et al., 2000; Southall & Taylor, 2001). Assuming constant road width, Guiducci (1998) has reported on an algorithm for the 3D road reconstruction from its image boundaries.

Of course, besides such ‘on-board’ approaches, video sequences from a stationary camera are also used, e.g. with the application of image processing and vision algorithms to traffic scenes for queue detection and vehicle classification or counting (Dailey et al., 2000). In particular, ordinary video cameras present certain advantages over other techniques for monitoring vehicle speed, e.g. with object tracking (Chun & Li, 2000), which represents a crucial parameter in studying the traffic character of freeways.

Most monoscopic methods cited above are characterised by the employment of cameras with known interior orientation (‘intrinsic camera’) parameters. Several camera calibration methods are available, while approaches have also been proposed which use the road itself as the calibration structure (Guiducci, 2000). But, wherever possible, the potential of uncalibrated cameras should be exhausted within flexible, low-cost approaches. For obvious reasons, the exterior information required should also be kept to a minimum to bypass the need for either point correspondences and targets, or additional sensors providing camera attitude. In speed measurement, for instance, the state-of-the-art in camera technology adopted by transportation agencies requires detailed intrinsic and extrinsic calibration of expensive cameras, and few efforts have been made to measure speed using sequences of uncalibrated images (Dailey et al., 2000; Pumrin & Dailey, 2002).

In this contribution approaches are presented and evaluated for measuring two types of quantities with single image techniques: lane width; and vehicle speed which, with known time intervals between frames, is obviously a problem of measuring distances. The video cameras used here are uncalibrated, in the sense that camera constant, principal point location and the image affinity parameters are irrelevant (radial lens distortion is not taken into account). Regarding exterior orientation, following ‘reasonable’ assumptions are made here: the ground in front of the camera is planar; cameras are fixed to the ground or the vehicle; images have negligible rotations about the vertical and camera axes (cf. Tao, 2001). Considering exclusively straight road segments, the only requirements for the 2D-2D image-to-road transformations in both cases (measurement of lane width and vehicle speed) are one known distance. It is currently under investigation how the approaches may be extended to include curving road segments or significant rotations about the vertical camera axis.

Numerical results presented in the existing literature as evaluations of algorithms measuring lane width and vehicle speed are indeed sparse. Thus, aim of this contribution was to present the mathematical models as well as to assess their performance with sufficient measurements. No automatic extraction technique has been applied here. These can be found in the existing literature, though even relatively straightforward tasks, such as lane tracking, may well prove unexpectedly difficult due to changing road and weather conditions (Southall & Taylor, 2001).

## 2. MEASUREMENT OF LANE WIDTH

To effectively manage existing road networks as regards operability and safety, sufficient information about their design parameters and installed equipment is needed; this concerns primarily older roads for which there is a considerable lack of data. A cost-effective road surveying system, designed at the Technical

University of Athens, has been used to survey segments of the national road network amounting to 1.300 km, 500 km of which have already been assessed (Psarianos et al., 2001). Installed in a mini-van, this system consists of a GPS system, inclinometer and three synchronised video cameras on the car roof, two looking sideward and one forward, from which composite images of three views of the road and surrounding area are produced. All information collected by the system is managed in a specially designed Transportation GIS. Here, the main photogrammetric task was to formulate and evaluate a simple approach for estimating lane width from geo-referenced frontal images.

### 2.1 Mathematical Model

Mounted stably on the roof of the car, the camera records with a horizontal axis, initially assumed parallel to the road axis. With the assumptions given above, the equation for estimating lane width from measurements on the image is very simple. The only a priori knowledge required is the height of the projective centre above ground. The basic geometry is seen in Fig. 1, in which O denotes the perspective center and M is the image center.

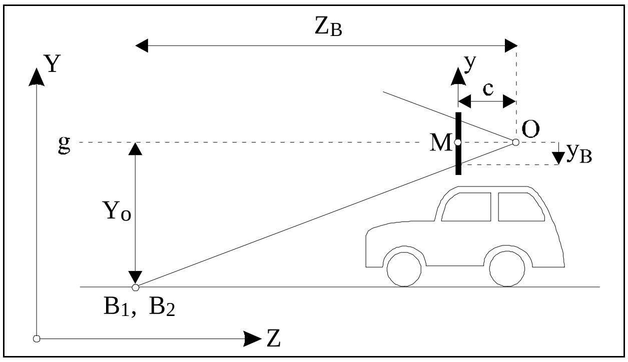


Figure 1. Recording geometry with horizontal camera axis.

The X axis in space and the x image coordinate axis are normal to the plane of the Figure. The camera constant is denoted by c, while $y_B$ is the y image coordinate of points $B_1$, $B_2$ on the road surface defining lane width. If $Y_O$ is the camera height above ground level, image scale at the distance $Z_B$ is expressed as

$$\frac{c}{Z_B} = -\frac{y_B}{Y_O} = \frac{\Delta x_B}{\Delta X_B} \tag{1}$$

with $\Delta X_B$ denoting lane width $B_1B_2$ and $\Delta x_B$ the corresponding length measured on the image (the principal point is ignored).

Unfortunately, this simple geometry is not retained as a moving vehicle oscillates on its suspensions. Hence, small instantaneous camera rotations are expected. Effects of small rotations $\kappa$ about the camera axis and $\phi$ about the vertical image y-axis may be practically neglected here. On the other hand, even small tilts $\omega$ about the horizontal camera x-axis are of importance, since the projective rays form small angles with the road, and large errors may occur. Introduction of a small $\omega$-angle into the collinearity equations modifies Eq. (1) as follows:

$$\frac{\Delta x}{\Delta X} = -\frac{y\cos\omega + c\sin\omega}{Y_O} \approx -\frac{y + c\omega}{Y_O} \tag{2}$$

It is noted that $\Delta x$ is not affected considerably by small rotations $\phi$ about the vertical axis, especially if $x_1 + x_2$ is a small quantity.

The obvious way to estimate an $\omega$-tilt is by using the vanishing point F in the Z-direction of depth, determined graphically on the frame by exploiting road delineation. In Fig. 2 it is seen that small $\omega$-tilts can be adequately approximated as follows (note that $y = -c\tan\omega$ is the equation of the horizon line):

$$\tan\omega = -\frac{y_F}{c} \approx \omega \quad \rightarrow \quad c\omega \approx -y_F \tag{3}$$

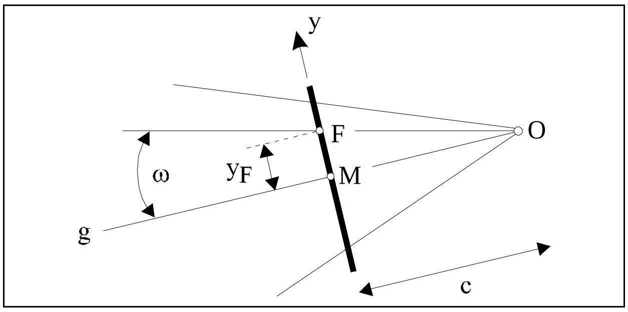


Figure 2. Image geometry with tilted camera axis.

If the x, y image measurements are performed directly in pixel dimensions according to Fig. 3, the introduction of Eq. (3) into Eq. (2) finally yields:

$$\Delta X = \frac{Y_O}{y - y_F} \Delta x \tag{4}$$

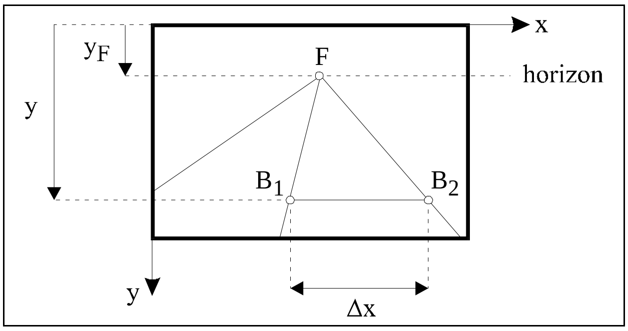


Figure 3. Measurements on the video frame.

Eq. (4) thus connects a lane width ? x measured on the image (at a certain y image coordinate) through the vanishing point F of the road direction with the corresponding actual lane width ? X. As opposed to the similar approach of Tao (2001), this equation is independent of the camera constant c which may remain unknown. Hence, the tilt $\omega$ itself cannot be recovered, yet its effect is taken into account (in all frames used, this effect is taken into account through the instantaneous vanishing point F). Besides, this equation uses only image coordinate differences $\Delta x$ and $\Delta y$, i.e. the principal point is also not necessary.

Furthermore, the eventual affine image deformation may also be bypassed. Rather than measuring the camera height $Y_O$ directly, it is precalibrated employing Eq. (4) reversely and a known lane width ? X (cf. Southall & Taylor, 2001). Of course, this value of $Y_O$ does not represent the actual camera height but is affected by image affinity. Yet, if this value of $Y_O$ is used afterwards in Eq. (4) for the same camera setup, the fact that measurements in the two image directions differ in scale has no effect upon the accuracy of subsequent lane width estimation.

### 2.2 Calibration and evaluation

Before employing the described approach on a routine basis, the calibration process and the accuracy had to be evaluated with an ordinary video camera (frame size: 640 x 512). For this purpose, 10 frames from different sites were first used to estimate camera height $Y_O$ through Eq. (4) from known widths Δ? (measured by tape with an estimated accuracy of ±2 cm). The final result was $Y_O$ = 1.937 m with a standard deviation σ = ±2.7 cm. It is noted that the actual camera height above the ground was about 1.8 m. As pointed out above, the estimated $Y_O$ value is subject to frame affinity (which here was about 8%). Subsequently, a total of 30 frames from ten different roads were chosen for assessing width estimation from Eq. (4) against tape measurement. Fig. 4 shows typical frames used for calibration and evaluation.

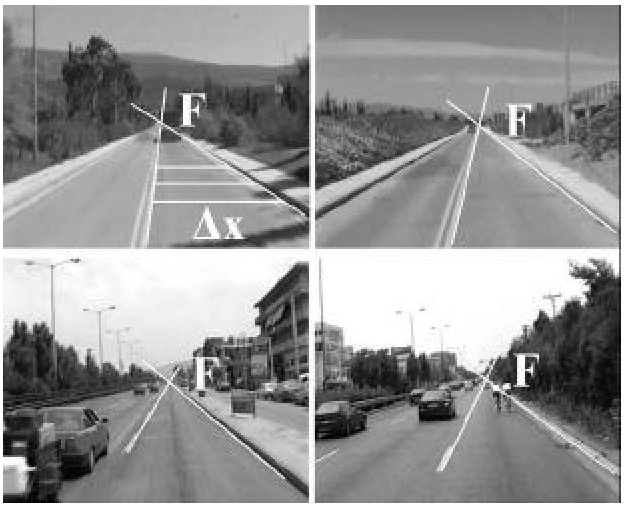


Figure 4. Video frames used for calibration and evaluation.

On every frame, separate Δx measurements were taken at five different y-levels on the image, and their corresponding ground widths were computed. The five ΔX estimates from each frame were treated individually, giving a mean difference and an RMS difference r from the corresponding reference ΔX values. For the five measurements on each image the standard deviation s was also computed. The overall results are presented in Table 5, whereby d denotes the absolute mean difference.

Table 5. Lane width accuracy from 30 frames

| mean difference | RMS difference | standard deviation |
|---|---|---|
| d = 2.3 cm | r = 4.7 cm | σ = ±3.8 cm |

The above results are considered as satisfactory since individual measurements of lane width are expected to have an accuracy r better than 5 cm (the largest RMS difference was 7.1 cm), while lane widths typically differ in steps of 25 cm. Image measuring errors and small uncorrected parts of ? -tilts, causing perspective distortions, are considered as the main sources of inaccuracy, as expressed in the repeatability σ of measurement. Obviously, an averaged width from more than one estimates per frame is generally expected to be closer to ground truth (d in Table 5). With this camera, reliable measurements were possible within a depth range of about 10–25 m in front of the vehicle.

It is clear that the reported accuracy characterises the particular setup used, depending primarily on image resolution and scale. Any other setup needs to be accordingly evaluated. On the other hand, accuracy is practically independent of road slope, as the camera axis is generally assumed to follow this slope, and small relative tilts are corrected by means of the vanishing points. It must be pointed out, however, that the validity of the approach holds only for the object plane on which the vehicle proceeds. In case of variable superelevation rates among lanes, the results are valid only for the lane on which the camera platform moves.

As mentioned already, this approach has been widely used on a routine basis (Psarianos et al., 2001). A different camera was employed here, separately calibrated as regards its height $Y_O$. In Fig. 6 frames of this application are shown.

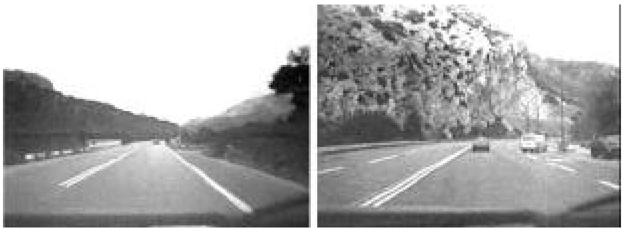

Figure 6. Typical video frames used in the actual application.

## 3. MEASUREMENT OF VEHICLE SPEED

The task was to develop a simple method for measuring vehicle speed, a crucial variable when studying the traffic character of a freeway to produce 'fundamental diagrams'. Actually, the traffic diagrams used in Greece stem from other countries, thus being rather inconsistent with the road conditions in this country and the temperament of its drivers.

Vehicle speed measurements on congested highways using an uncalibrated camera have already been reported (Dailey et al., 2000; Pumrin & Dailey, 2002). In these cases, the mean vehicle dimensions were used for scaling purposes; thus, only estimates for time-averaged mean vehicle speed were obtained. Contrary to this, the task here was to measure the speed of individual cars in order to obtain detailed information on speed distribution.

### 3.1 Full projective transformation with control points

The images used here had been acquired for a previous study of the traffic character of freeways (Chorianopoulos, 2001). Traffic flow had been recorded from a 10 m high structure over a freeway with three lanes in each stream. A digital video camera was used on different occasions, looking centrally along the axis of one stream with a certain downward tilt against the horizontal. The time interval between successive frames, whose dimensions were 768 x 576, was known as 25 frames/sec. Thus, speed in all three lanes could be estimated simply by measuring the vehicle translation between frames (here again assuming flat ground).

In order to measure distances covered by cars between frames, Chorianopoulos (2001) has applied full 2D–2D projective transformation based on ground control points to assess the potential of a conventional photogrammetric approach. Using 20 geodetic control points, adjustments for the 8 projective coefficients had RMS errors not larger than 20 cm. One out of about every ten frames were used for each vehicle to provide an average of six successive speed estimates within an actual distance of about 75 m. Among the numerous cars having crossed the field of view in the two full hours of recording, several hundreds of them were measured. The overall standard deviation of $\sigma_S$ = ±2 km/h (assuming constant speed) is considered as very satisfactory and represents the estimated precision of individual measurements. Mean speeds for each vehicle are expected to be more accurate. Indeed, the accuracy of photogrammetric speed estimation was evaluated against speed measurements using a GPS system on a moving vehicle which was imaged three times. The differences of mean speeds were below 1 km/h. These experiments indicate the potential of single image metrology. Yet, simpler procedures with no need for control points are obviously required.

### 3.2 Affine transformation for 1D measurements

**3.2.1 Affine rectification from two vanishing points** Once the image horizon of a plane is defined, the affine properties of this image can be recovered. A horizon line is commonly identified through the vanishing points in two orthogonal directions on a plane providing the vanishing line or the image of the line at infinity $I_\infty$. The projective transformation relating image to plane coordinates is a homography, expressed as follows in homogeneous representation (Hartley & Zisserman, 2000):

$$\mathbf{Hx} = \mathbf{X} \quad \text{or} \quad \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ 1 \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ 1 \end{bmatrix} \tag{5}$$

whereby $\mathbf{H}$ is a 3x3 matrix with 8 coefficients, $\mathbf{x} = (x_1, x_2, 1)^T$ is an image point, $\mathbf{X} = (X_1, X_2, 1)^T$ is a point on the ground plane. The vector $(g, h, 1)^T$ describes the vanishing line of the ground plane ($I_\infty$) and is found from the cross product of two vanishing points (Liebowitz et al., 1999). The knowledge of $I_\infty$ allows to remove pure projectivity, i.e. allows affine rectification (correct length ratio on parallel lines). The orthogonality of the two directions restores angles. Here one faces a 1D problem, i.e. one is interested in measuring distances in a single direction to estimate vehicle speed. Hence, there is no need to correct aspect ratio for securing uniform scale. Only the scale along the road axis has to be restored, for which one known ground distance in this direction suffices.

**3.2.2 Affine rectification from one vanishing point** However, the main question posed here concerns the kind of rectifications possible in case only one vanishing point is available. Indeed, in several cases lines do not suffice for determining two vanishing points. In Fig. 7, which presents an example of the images used here, parallel lines have been identified only along the road axis (ground Y-axis), as lane demarcations cannot always be trusted as regards the orthogonal direction (ground X-axis). In this context, two main assumptions can be made.


Figure 7. The vanishing point of the road.

- It is first assumed that the image plane is practically parallel to the ground X-axis (as in the present case; cf. Fig. 7). Hence, the second vanishing point is at infinity, i.e. lines orthogonal to the road axis are imaged parallel to the x-image axis. Vanishing points $F_1$ in the direction of the road axis and $F_2$, assumed at infinity, are expressed as follows on the image plane:

$$\mathbf{F}_1 = \begin{bmatrix} f_1 \\ f_2 \\ 1 \end{bmatrix} \qquad \mathbf{F}_2 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

Points $F_1$ and $F_2$ define $I_\infty$ (cross product), a line parallel to the image x-axis. The point at infinity in the direction orthogonal to the road axis is thus forced to be transformed through $\mathbf{H}$ to the point at infinity of the image x-axis:

$$\mathbf{H} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

As mentioned, the orthogonality constraint provides the remaining coefficients of $\mathbf{H}$. Having set coefficients c and f (since they concern pure translation) to zero, it can be proved that finally:

$$\mathbf{H} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & 1 \end{bmatrix} = \begin{bmatrix} 1 & -f_1/f_2 & 0 \\ 0 & 1 & 0 \\ 0 & -1/f_2 & 1 \end{bmatrix} \tag{7}$$

As already pointed out, no need arises here for correcting aspect ratio. However, visual reasons might dictate its modification. A scale factor m, suitably chosen in each case, will 'improve' the aspect ratio of the rectification (without actually restoring it). This modification is described by matrix $\mathbf{M}$, contributing to the final transformation matrix $\mathbf{H}_M$:

$$\mathbf{M} = \begin{bmatrix} m & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \rightarrow \quad \mathbf{H}_M = \mathbf{MH} \tag{8}$$

A measured distance along the road axis relates the pixel size of the rectified image to the ground units in this direction.

However, a direct approach is also possible. Similar to Eq. (6), the transformation for the finite vanishing point $F_1$ is:

$$\mathbf{H} \begin{bmatrix} f_1 \\ f_2 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{9}$$

From Eqs. (6) and (9), $\mathbf{H}$ may be directly determined in one step without computing the vanishing line etc.

- In case the previous assumption is invalid, i.e. both vanishing points are finite but only one can be identified on the image, with the above approach ground distances can be measured only on the specific line of the known reference length. Parallelism of lines in the direction of the road axis (ground Y-axis) will be restored, however their scale will not be uniform. The answer to this can be provided by the 'construction' of a second vanishing point from two known lengths.

**3.2.3 Construction of a second vanishing point** As mentioned already, a second vanishing point is needed to allow affine rectification when the image planes are not parallel to the ground X-axis. Following Fig. 8, assume two known distances *d* and *p* on ground lines D and P running parallel to the road axis (Y-axis); on the image they converge to point $F_1$. By exploiting the cross ratio, from length *p* one may compute a ground length *q* = *d* on line P. Evidently, these two equal and parallel line segments *d* and *q* define two parallel ground lines. On the image, these lines define their vanishing point $F_2$ which lies on the horizon.

The above are illustrated in Fig. 9. On the left, an image patch is rectified from only one vanishing point $F_1$. Parallelism has been restored only along the y-axis. Extraction of metric information is possible only on the line of the known length. On the right, one may see the outcome of affine rectification from two known lengths, described above. Here, parallelism has been restored in all directions. Angles can be restored only if the angle between the two directions is known. Measurement is here possible on all lines along the correctly scaled y-direction.

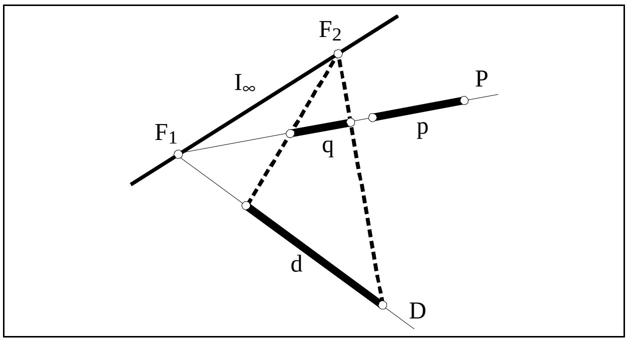


Figure 8. Vanishing point $F_2$ from lengths *a*, *b* on parallel lines.

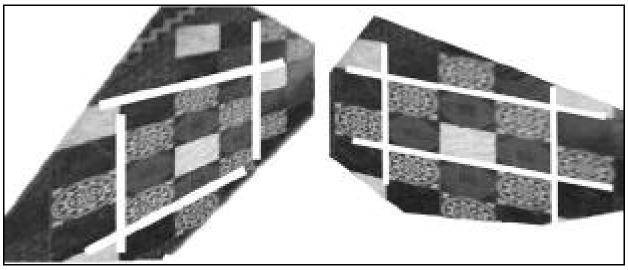

Figure 9. Rectification with one and two vanishing points.

This approach, requiring a second known length on the ground, is important as it bypasses the constraint on camera orientation. In the present case, however, images were assumed to have only a tilt about the horizontal x-axis, hence the approach with one vanishing point and one known distance was actually applied.

### 3.3 Practical evaluation

The performance of the approach, laid out in section 3.2.2, for 1D measurement based on one finite vanishing point (that in the direction of the road axis, with the second assumed at infinity) has been evaluated against 2D-2D measurement (section 3.1). A total of 11 vehicles in all three lanes were followed, and their speed was found from 4–8 frames. Three independent estimations were made, based on three different known distances (seen in Fig. 10) to establish the repeatability of results.


Figure 10. Known distances *a*, *b*, *c* used for speed estimation.

The vehicle's shadow was manually measured on the first frame and was then automatically followed in subsequent frames with a simple correlation technique. This has been facilitated by the use of rectified images. In Fig. 11, the affine transformations of three frames are shown.

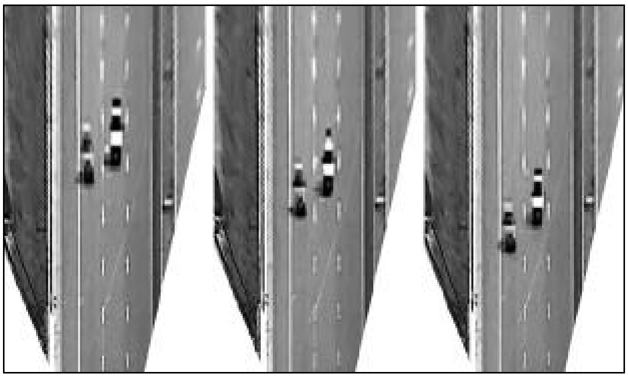

Figure 11. Affine rectifications of successive frames.

The results are seen in Table 12, which presents mean speed v and standard deviation σ from all frames of each vehicle. Only very few outlying estimates have been rejected, namely from the far end of the road where image scale is too small and measuring errors cause very large displacements.

Table 12. Speed v estimation in km/h from 1D measurements using three different known distances *a*, *b*, *c* (11 vehicles)

| 1D | | | | | | 2D | |
|---|---|---|---|---|---|---|---|
| *a* | | *b* | | *c* | | | |
| v | σ | v | σ | v | σ | v | σ |
| 95 | ±2 | 94 | ±2 | 95 | ±2 | 95 | ±1 |
| 110 | ±2 | 110 | ±2 | 110 | ±2 | 109 | ±1 |
| 118 | ±2 | 117 | ±2 | 118 | ±2 | 118 | ±2 |
| 99 | ±2 | 99 | ±2 | 100 | ±2 | 98 | ±1 |
| 115 | ±1 | 115 | ±1 | 116 | ±1 | 116 | ±1 |
| 122 | ±2 | 122 | ±2 | 120 | ±2 | 122 | ±2 |
| 146 | ±3 | 146 | ±3 | 146 | ±3 | 144 | ±2 |
| 103 | ±1 | 102 | ±1 | 103 | ±1 | 103 | ±1 |
| 133 | ±2 | 132 | ±2 | 133 | ±2 | 133 | ±1 |
| 132 | ±1 | 131 | ±1 | 132 | ±1 | 131 | ±2 |
| 156 | ±3 | 156 | ±3 | 157 | ±3 | 155 | ±1 |

The results indicate that the simple approach of affine rectification using one vanishing point and one known distance (under the assumption that the image plane is parallel to the X-axis of the road) compare very well with metric data derived from full 2D-2D projective transformation (the validity of which has been established with GPS measurements).

## 4. CONCLUDING REMARKS

In this contribution methods have been presented for extracting metric data form single uncalibrated images (in the specific context of road and traffic scenes). Based on a combination of photogrammetric and computer vision approaches, the methods are very simple requiring minimal external information (one known distance) if 'reasonable' assumptions are adopted. In both cases images are subject to affine deformations, yet 1D measurements are possible in the properly scaled direction. It has been further demonstrated that both methods are capable of providing metric results of satisfactory accuracy.

Of course, important questions still wait to be addressed. For instance, lane width estimation is limited to linear road segments.

It needs to be investigated how reliable measurements may be also made on curving road sections (e.g. curve widening). Here, on the other hand, we have focused on geometric aspects, and a minimum of automation has been used. Image processing algorithms for the automatic tracking of vehicles and lane delineation has to be introduced, to allow wider exploitation of single uncalibrated images in the present framework.

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