DESIGN OF A RUNWAY CROSSING : OPTIMALISATION OF THE DIFFERENCE IN HEIGHT BETWEEN THE TOPS OF BOTH RUNWAY PROFILES

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ABSTRACT

Runways are generally constructed in a transversal roof profile with rounded top and 1.5% side slope to prevent standing water. Where runways cross some kind of bump will occur in both runways. The effect of these bumps to the vertical acceleration of aircraft can be calculated with a two mass spring simulation program.
This paper describes a study on optimalisation of the difference in height **ΔH** of the tops of both runway profiles at an existing runway crossing on a military airfield in the Netherlands.
For a given traffic distribution landings and take-off's are simulated calculating the vertical accelerations caused by the disturbance of the longitudinal profiles at the crossing. The accelerations of the Centre of Gravity of the aeroplane model, expressed in **g** (where g is the acceleration of gravity ≈ 10 m/s²), are compared to the vertical accelerations that occurs on an average runway (called "Back Ground Values") and expressed in a multiplier **M**. It is considered that the total effect of the crossing to the fleet can be expressed by the **Σ M x N**, where N is the number of movements (take-off's or landings) of a given aeroplane.
The optimum value of **ΔH** is where **Σ M x N** reaches a minimum. To find this optimum a second degree function of $M(\Delta H) = a(\Delta H-b)^2+c$ is assessed for every movement through three points of simulation. Doing so it is considered that where M<1 the crossing "falls back into the back ground accelerations" and will not be taken into account.
The results of this calculations give an optimum for **ΔH = 28.4 mm** and a conclusion that ΔH may not exceed this value. This result is only valuable for the specified aircraft movement distribution and may not be used for other situations.
A second conclusion is that even for the optimum **ΔH** some accelerations caused by the crossing exceed g = 1 and will cause damage to the aircraft.

Introduction

At a military airfield in The Netherlands there are 2 runways crossing each other. Due to a planned reconstruction the question raised how to construct the runway crossing in such a way that the bumps in both runways causes minimum troubles.
To solve this problem Aircraft Movement Simulations were made with the APRAS computer program from APR Consultants, Inc.

Local situation

The Main Runway 24 – 06 is 50 meters wide and 2400 meters long. The crossing is located at 600 meters from the 24 Runway End.
The Secondary Runway 27 – 09 is 30 meters wide and 2000 meters long. The crossing is located at 600 meters from the 27 Runway End.
To give sufficient drainage to rain water both runways are constructed in roof profile with rounded top and side slopes of 1.5%. This will also be after reconstruction.
Wind is mostly coming from South-West to West.

Problem analyses

At the runway crossing the roof profile of the Secondary Runway meets the profile of the Main Runway with the top mostly a little bit lower than the top of the Main Runway. The problem can be brought back to the question: “What is theoretically the best difference in height between the top of the Main Runway profile and the top of the Secondary Runway?”

Operations

The Airfield is an F-16 Fighter Base also used for some Air Transport. The mean weekly flight operations (Take-Off and Landing) are 200 F-16’s, 10 General Aviation mainly being C-130 and B737 Civil Aeroplanes and 1 DC-10-30.
20% of the movements are made to and from the Secondary Runway.
10% of the F-16 Take-Off’s from the Main Runway are so called Formation Take-Off’s where 2 aeroplanes take-off at the same time, each using half of the runway width.
No Formation Take-Off’s are made from the Secondary Runway.
80% of the movements are made in the direction South West and West.

Aircraft Modeling and Back Ground Vertical Accelerations

The version of the APRas program used contains 3 F-16 models. The heaviest one, F-16 I (Air-to-Ground configuration) is used, because this gives the highest vertical accelerations of the three.
For the General Aviation the B3 model with 2 wing-mounted engines is used.
And for the DC-10 the D model is used.
Taken into consideration that Aircraft Movements on an average runway always course a certain amount of vertical accelerations and that there will be no problems if the accelerations coursed by the runway crossing are equal or lower than these “Back Ground Accelerations”, Take-Off and Landing Simulations were done with all of these models on the Average Runway that is provided within the program.

This simulations also gave the required runway length for the operations, so it could be analyzed what operations are being effected by the runway crossing. The results of the simulations are given in table 1.

Simulation	g at CG	g at PS	RQF	Length [m]
F-16 Take-Off	0.59	0.51	2.79	1200
F-16 Landing	0.53	0.52	3.92	800
B3 Take-Off	0.43	0.46	2.43	1700
B3 Landing	0.37	0.54	2.75	900
D Take-off	0.12	0.28	1.18	1600
D Landing	0.25	0.52	2.19	1000

Table 1: Simulation results on Average Runway
G at CG = the vertical acceleration [g] at the Center of Gravity of the aeroplane.
G at PS = the vertical acceleration [g] at Pilot Seat
RQF = Ride Quality Factor
Length = Distance used for the specified operation in meters.

A typical plot of the accelerations on an average runway are given in figure 1.
The waves occur during the complete movement.

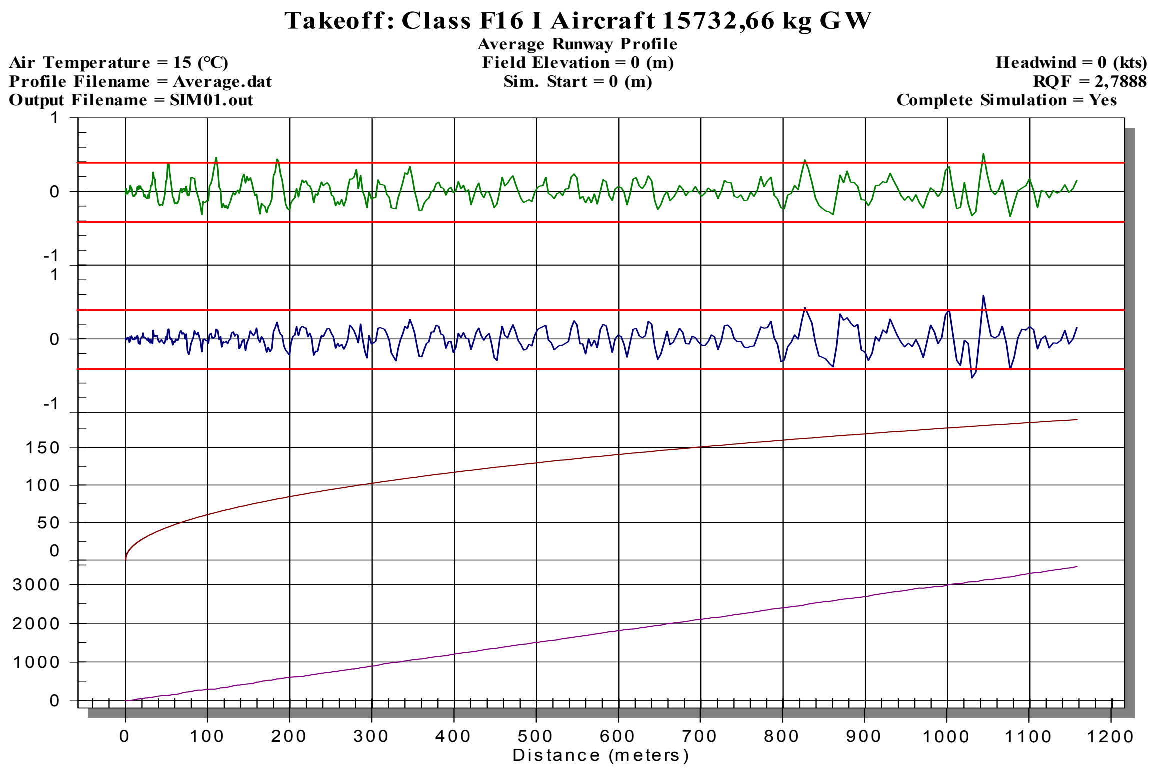
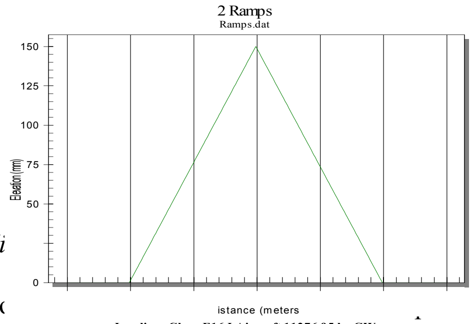
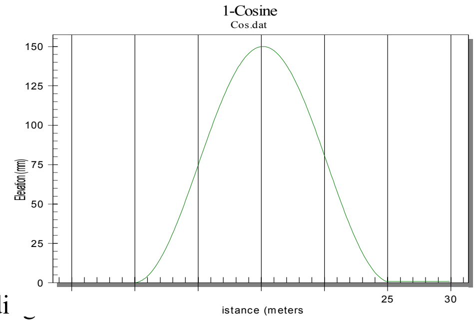


Figure 1: Take-Off Simulation on Average Runway

Modeling of the crossing

There are several ways of modeling the bump of the crossing. The first idea is to use 2 ramps, one up and one down, as shown in figure 2. In practice the hard corners will be rounded off, so the possibility in the APRas program of using a 1-Cosine bump is more elegant and more realistic, although the truth will be somewhere between these two alternatives.





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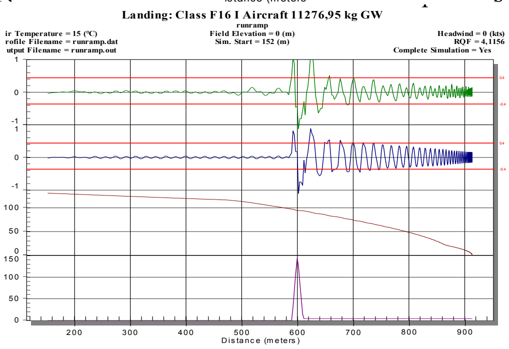


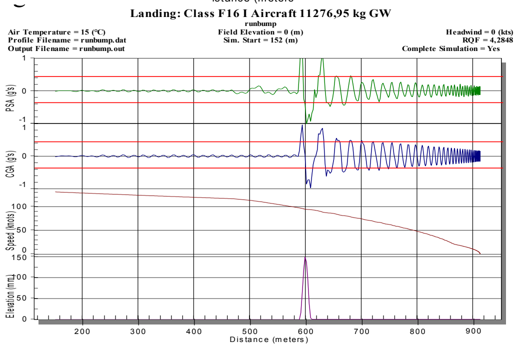


Figure 4: Effect of 2 ramps

Figure 5: Effect of 1-cosine bump

There is no significant difference to see, also not in the maximum accelerations. So for all simulations the 1-Cosine bump is used. After all there is more interest in the relative effect than the absolute values.

	G at CG	G at PS	RQF
Ramps	1.11	1.20	4.12
Bump	0.97	1.40	4.28

Table 2: The difference between profile models.

Aircraft movements and crossing passages

According the above paragraphs the next aircraft movements are to be calculated, looking over 25 weeks to come to round figures. The Distance from Center Line (DCL) is the location where the runway profile has to be calculated. For large aircraft this is the position of the main gear (half the tread) and for F-16 this is the center of the airplane. Not all movements are influenced by the crossing. For instance the Main Runway top will be higher than the top of the Secondary Runway, so single F-16 movements on the Main Runway are not involved by the Runway Crossing.

Aircraft	Movement	Runway	Direction	Number	DCL	Required Length	Available to Xing	Remarks
F-16	Single TO	Main	24	2880	0	1200	600	On runway top
F-16	Form. TO	Main	24	320	12.5 m	1200	600	
F-16	Landings	Main	24	3200	0	800	600	On runway top
F-16	Single TO	Main	06	720	0	1200	1800	On runway top
F-16	Form. TO	Main	06	80	12.5 m	1200	1800	Before Crossing
F-16	Landings	Main	06	800	0	800	1800	On runway top
F-16	TO (single)	Sec	27	800	0	1200	600	
F-16	L	Sec	27	800	0	800	600	
F-16	TO	Sec	09	200	0	1200	1400	Before Xing
F-16	L	Sec	09	200	0	800	1400	Before Xing
B3	TO	Main	24	160	2.60 m	1700	600	
B3	L	Main	24	160	2.60 m	900	600	
B3	TO	Main	06	40	2.60 m	1700	1800	Before Xing
B3	L	Main	06	40	2.60 m	900	1800	Before Xing
B3	TO	Sec	27	40	2.60 m	1700	600	
B3	L	Sec	27	40	2.60 m	900	600	
B3	TO	Sec	09	10	2.60 m	1700	1400	
B3	L	Sec	09	10	2.60 m	900	1400	Before Xing
D	TO	Main	24	16	5.30 m	1600	600	
D	L	Main	24	16	5.30 m	1000	600	
D	TO	Main	06	4	5.30 m	1600	1800	Before Xing
D	L	Main	06	4	5.30 m	1000	1800	Before Xing
D	TO	Sec	27	4	5.30 m	1600	600	
D	L	Sec	27	4	5.30 m	1000	600	
D	TO	Sec	09	1	5.30 m	1600	1400	
D	L	Sec	09	1	5.30 m	1000	1400	Before Xing

Table 3: Aircraft movements in 25 weeks (to get round figures).

Table 3 makes clear that only 13 of the 26 different aircraft movements are involved in the design of the crossing.

Profile assessment

To reduce the number of simulations it is believed that the reaction of the aircraft to the height of the bump can be expressed good enough for this goal by a two degree algorithm, assessable by 3 points. So for all of the 13 movements 3 profiles were assessed to do simulations (a minimum and a maximum bump and one in between).
It will be clear that for Landing and Take-Off in the same situation the same profile can be used, so 3 x 8 = 24 profiles were assessed. And since no movement takes 2000 meters a standard profile length of 2000 m is chosen.
Since the side slope is fixed to 1.5% the profiles depend on the Distance to the Center Line (DCL) and the difference in height between the tops of both runways, Delta H (ΔH).

Simulations

The desired aircraft movements were simulated with the assessed runway profiles and the results were compared to the Back Ground values. It appeared that the Ride Quality Factor (RQF) is no good comparison factor for this problem, because this factor is dependant to the place of the bump on the runway. The acceleration (g) of the Pilot Seat is not right calculated, especially not for bigger airplanes because the nose wheel follows another, more smooth, profile than the main gear. So finally is chosen for the acceleration (g) at the Center of Gravity (CG). A multiplier (M) is calculated to express the difference between the Calculated g at CG and the related background value. The results of these calculations are presented in table 4.

Profiles					Bump				BACKGROUND VALUES			**Simulations**			Multiplier M
Nr	Main1 /Sec2	ΔH [mm]	Class	DCL [m]	Length [m]	Height [mm]	St.pt. [m]	TO / L	g at CG	g at PS	RQF	**g at CG**	**g at PS**	**RQF**	g at CG
M0F	1	0	F16-I	12.5	**28.875**	**187.5**	**600**	TO	0.59	0.51	2.79	2.08	2.79	17.36	3.53
M1F	1	50	F16-I	12.5	**21.175**	**137.5**	**600**	TO	0.59	0.51	2.79	0.99	1.44	3.36	1.68
M2F	1	100	F16-I	12.5	**13.475**	**87.5**	**600**	TO	0.59	0.51	2.79	0.67	0.99	2.52	1.14
M0B	1	0	B3	2.6	**6.006**	**39**	**600**	TO	0.43	0.46	2.43	0.39	0.69	1.33	<1
M1B	1	20	B3	2.6	**2.926**	**19**	**600**	TO	0.43	0.46	2.43	< Background			<1
M2B	1	39	B3	2.6	**0**	**0**	**600**	TO	0.43	0.46	2.43	0	0	0	<1
M0B	1	0	B3	2.6	**6.006**	**39**	**600**	L	0.37	0.54	2.75	0.36	0.44	1.8	<1
M1B	1	20	B3	2.6	**2.926**	**19**	**600**	L	0.37	0.54	2.75	< Background			<1
M2B	1	39	B3	2.6	**0**	**0**	**600**	L	0.37	0.54	2.75	0	0	0	<1
M0D	1	0	D	5.3	**12.243**	**79.5**	**600**	TO	0.12	0.28	1.18	0.35	0.9	1.26	2.92
M1D	1	40	D	5.3	**6.083**	**39.5**	**600**	TO	0.12	0.28	1.18	0.17	0.29	0.49	1.42
M2D	1	79.5	D	5.3	**0**	**0**	**600**	TO	0.12	0.28	1.18	0	0	0	0
M0D	1	0	D	5.3	**12.243**	**79.5**	**600**	L	0.25	0.52	2.19	0.24	0.61	1.22	<1
M1D	1	40	D	5.3	**6.083**	**39.5**	**600**	L	0.25	0.52	2.19	0.15	0.28	0.67	<1
M2D	1	79.5	D	5.3	**0**	**0**	**600**	L	0.25	0.52	2.19	0	0	0	<1
S0F	2	0	F16-I	0	**0**	**0**	**600**	TO	0.59	0.51	2.79	0	0	0	0
S1F	2	50	F16-I	0	**7.7**	**50**	**600**	TO	0.59	0.51	2.79	0.33	0.6	1.34	0.56
S2F	2	100	F16-I	0	**15.4**	**100**	**600**	TO	0.59	0.51	2.79	1.02	1.12	2.89	1.73
S0F	2	0	F16-I	0	**0**	**0**	**600**	L	0.53	0.52	3.92	0	0	0	0
S1F	2	50	F16-I	0	**7.7**	**50**	**600**	L	0.53	0.52	3.92	0.79	0.57	2.79	1.49
S2F	2	100	F16-I	0	**15.4**	**100**	**600**	L	0.53	0.52	3.92	0.92	1.27	3.87	1.74
S0B	2	0	B3	2.6	**6.006**	**39**	**600**	TO	0.43	0.46	2.43	0.39	0.69	1.33	0.91
S1B	2	50	B3	2.6	**13.706**	**89**	**600**	TO	0.43	0.46	2.43	0.74	1.26	2.16	1.72
S2B	2	100	B3	2.6	**21.406**	**139**	**600**	TO	0.43	0.46	2.43	0.76	1.03	2.45	1.77
S0B	2	0	B3	2.6	**6.006**	**39**	**600**	L	0.37	0.54	2.75	0.36	0.44	1.79	0.97
S1B	2	50	B3	2.6	**13.706**	**89**	**600**	L	0.37	0.54	2.75	0.68	1.04	3.34	1.84
S2B	2	100	B3	2.6	**21.406**	**139**	**600**	L	0.37	0.54	2.75	0.95	1.24	4.24	2.57
S0D	2	0	D	5.3	**12.243**	**79.5**	**600**	TO	0.12	0.28	1.18	0.35	0.9	1.26	2.92
S1D	2	50	D	5.3	**19.943**	**129.5**	**600**	TO	0.12	0.28	1.18	0.52	1.38	1.95	4.33
S2D	2	100	D	5.3	**27.643**	**179.5**	**600**	TO	0.12	0.28	1.18	0.62	1.41	2.02	5.17
S0D	2	0	D	5.3	**12.243**	**79.5**	**600**	L	0.25	0.52	2.19	0.24	0.62	1.22	0.96
S1D	2	50	D	5.3	**19.943**	**129.5**	**600**	L	0.25	0.52	2.19	0.32	0.86	2.03	1.28
S2D	2	100	D	5.3	**27.643**	**179.5**	**600**	L	0.25	0.52	2.19	0.36	1.04	2.51	1.44
S0B9	2	0	B3	2.6	**6.006**	**39**	**1400**	TO	0.43	0.46	2.43	0.45	0.27	0.61	1.05
S1B9	2	50	B3	2.6	**13.706**	**89**	**1400**	TO	0.43	0.46	2.43	0.52	0.78	1.4	1.21
S2B9	2	100	B3	2.6	**21.406**	**139**	**1400**	TO	0.43	0.46	2.43	0.55	1.09	1.67	1.28
S0D9	2	0	D	5.3	**12.243**	**79.5**	**1400**	TO	0.12	0.28	1.18	0.23	0.54	0.53	1.92
S1D9	2	50	D	5.3	**19.943**	**129.5**	**1400**	TO	0.12	0.28	1.18	0.33	0.71	0.88	2.75
S2D9	2	100	D	5.3	**27.643**	**179.5**	**1400**	TO	0.12	0.28	1.18	0.36	0.89	1.01	3.00

Table 4: Results of Aircraft Movement Simulations; Comparison to Background Values.

To find an optimum value for ΔH a second degree formula $M=a(\Delta H-b)^2+c$ (formula 1) is considered good enough to describe the relation between the multiplier M and ΔH for the various movements. The parameters a, b and c can be calculated with the results of the 3 simulations of the same movement with different ΔH.
To express the total effect of the bump to the whole fleet the calculated M with formula 1 is multiplied by the number of movements given in table 3 and then summarized to one value dependant of ΔH. Doing this it is considered that values of M<1 are not taken into account, because the effect of the bump is smaller then the vertical accelerations that occur on an average runway (the bump will not be noticed).
The results of these calculations are given in table 5 and figure 6.

Sum M x N =	**1199**	**1139**	**1015**	**922**	**1741**	**1846**	**1926**	**1970**	**2007**	**2969**	**3162**	**3351**
ΔH =	0	10	20	28.4	30	40	50	60	70	80	90	100
Number												
320	1128	976	842	741	723	622	537	469	417	383	365	363
F16-24-TO												
160												
B3-24-TO												
160												
B3-24-L												
Number												
16	47	41	35	30	29	23	17	0	0	0	0	0
D-24-TO												
16												
D-24-L												
Number												
800	0	0	0	0	0	0	0	0	0	950	1157	1383
F16-27-TO												
Number												
800	0	0	0	0	835	1034	1192	1311	1390	1430	1429	1389
F16-27-L												
Number												
40	0	45	53	59	59	65	69	72	73	74	73	71
B3-27-TO												
Number												
40	0	46	53	59	60	67	74	80	86	92	97	103
B3-27-L												
Number												
4	12	13	14	15	15	16	17	18	19	20	20	21
D-27-TO												
Number												
4	0	4	4	5	5	5	5	5	5	6	6	6
D-27-L												
Number												
10	10	11	11	12	12	12	12	12	12	13	13	13
B3-09-TO												
Number												
1	2	2	2	2	2	3	3	3	3	3	3	3
D-09-TO												

Table 5: The accumulated effect of the bump on the whole fleet dependent of ΔH

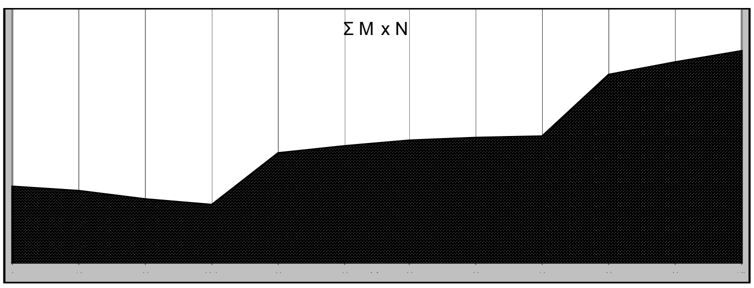


Figure 6: Graphic impression of accumulated effect.

It is clearly to see that with $\Delta H > 28.4$ mm the crossing becomes effective for F-16's landing on the secondary runway (in the direction 27).

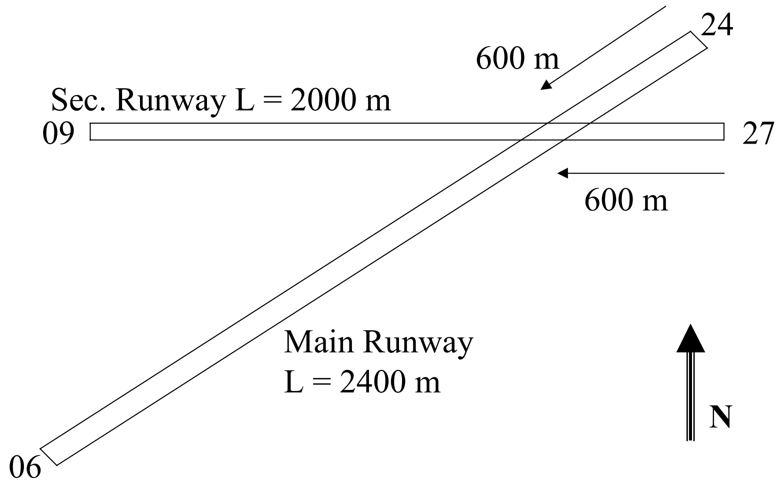
Conclusions and follow-up

Runway crossings are to be avoided. They always give unacceptable vertical accelerations and corresponding gear loads. For the specific situation in this study a certain optimum for the difference in height between the tops of the two runway profiles is found at 28 mm.

Since the vertical accelerations even at this optimum are still too high, further experiments will be done by changing the longitudinal profiles of the runways.

Appendix 1: Some figures for better understanding

Local Situation



Schematic Runway Crossing